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Operation

HARDTACK

April - October 1958

Project 1.9

355492

LOADING ON BURIED SIMULATED STRUCTURES IN HIGH-OVERPRESSURE REGIONS (U)

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OPERATION HARDTACK—PROJECT 1.9

LOADING ON BURIED SIMULATED STRUCTURES IN HIGH-OVERPRESSURE REGIONS (U)

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ABSTRACT

The objective was to study some of the factors affecting the transmission of air-blast-induced pressure through soil and the loading produced on buried structures by such pressures in the high-pressure region (approximately 250 psi).

Factors studied by this project were: (1) the attenuation of pressure in a sand deposit when the water table is a few feet below the ground surface; (2) the effect of duration of positive phase of blast on the pressure transmitted through such a soil; (3) the effect of structure flexibility on the pressure acting on structures buried in such a soil; and (4) the relationship between horizontal and vertical pressures in such a soil.

The project employed 43 devices, each a rigid cylinder having one rigid end and one deformable-diaphragm end. Three thicknesses of diaphragm were used to simulate structures of different flexibilities. The devices were buried at depths ranging from 0 to 20 feet at each of two locations at the Eniwetok Proving Ground. The locations were chosen to give a predicted ground surface overpressure of about 250 psi from each of two shots, Cactus and Koa. The predicted pressures were based on predicted yields of 16 kt for Shot Cactus and 1.4 Mt for Shot Koa. The actual yield for Shot Cactus was 18 kt and for Shot Koa 1.3 Mt. The average measured peak surface overpressures at the locations of the drums were 304 psi for Shot Cactus and 240 psi for Shot Koa.

Static strain-gage readings and permanent deflection measurements were made on the diaphragms before and after the test. Transient-strain and maximum-deflection measurements were made on the devices having the stiffest diaphragms. Additional measurements were made by surface-pressure and water-level gages. A laboratory program was conducted to calibrate the field test devices.

The attenuation of air-induced pressure with depth was obscured by the apparent existence of a large-magnitude horizontal water-transmitted shock; however, the following results were observed: The attenuation of the air-induced pressure was about 20 percent in the first 5 feet; this attenuation apparently ceased within 5 feet below the water table. In this particular soil deposit, there was no appreciable effect of the difference between the positive-phase durations of the pressure pulses from Shots Cactus and Koa. Above the water table, the horizontal pressure was about 50 percent of the vertical pressure, whereas, a few feet below the water table the horizontal pressure became approximately equal to the vertical pressure. The flexibility of the diaphragms had a large effect on the pressures acting on them whether above or below the water table. The simplified theory developed in Reference 1 gave reasonable predictions of the pressures on the diaphragms.

FOREWORD

This report presents the final results of one of the projects participating in the military-effect programs of Operation Hardtack. Overall information about this and the other military-effect projects can be obtained from ITR-1660, the "Summary Report of the Commander, Task Unit 3." This technical summary includes: (1) tables listing each detonation with its yield, type, environment, meteorological conditions, etc.; (2) maps showing shot locations; (3) discussions of results by programs; (4) summaries of objectives, procedures, results, etc., for all projects; and (5) a listing of project reports for the military-effect programs.

PREFACE

The work reported herein was planned and carried out by personnel of the Structural Research Laboratory of the University of Illinois under Contract AF 29(601)-544 with the Air Research and Development Command. All of the work under the contract was technically monitored by the Structures Division, Research Directorate, Air Force Special Weapons Center.

The project was under the general direction of Dr. N. M. Newmark, Head, Department of Civil Engineering, and under the immediate supervision of G. K. Sinnamon, Associate Professor of Civil Engineering. Other personnel of the Structural Research Laboratory who contributed materially to the project were G. F. McDonough, R. N. Wright, and S. L. Paul. Most of the detailed planning, and all of the analytical studies, were the responsibility of G. F. McDonough.

Dynamic instrumentation and ground-surface-pressure measurements were furnished this project by the Ballistic Research Laboratories (BRL), Aberdeen Proving Ground, Maryland. The field crew, which provided these services, was under the direction of Mr. J. J. Meszaros.

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INTRODUCTION

1.1 OBJECTIVE

The objective was to study some of the factors affecting the transmission of air-blast-induced pressure through soil and the loading produced on buried structures by such pressures in the high-pressure region (approximately 250 psi).

Factors studied by this project were: (1) the attenuation of pressure in a sand deposit when the water table is a few feet below the ground surface; (2) the effect of duration of positive phase of blast on the pressure transmitted through such a soil; (3) the effect of structure flexibility on the pressure acting on structures buried in such a soil; and (4) the relationship between horizontal and vertical pressures in such a soil.

1.2 BACKGROUND

During previous nuclear and high-explosive tests, which included both above- and below-ground detonations, several projects have been conducted to study the phenomena of pressure transmission through soil. The majority of these projects studied only the soil pressures produced by such detonations; only a few included a study of the loads produced on underground structures or structural models. The information obtained has not been sufficient either to permit the full determination of the factors involved in pressure transmission or to provide satisfactory methods of predicting the loads on underground structures. The inadequacies of most previous studies were caused by their limited scope. This was particularly the case in the studies involving underground structures, because the high cost of such structures has always necessitated using a small number of them in any test program.

During Operation Plumbbob at the Nevada Test Site (NTS), devices similar to those used by this project were used by Project 1.7 for an extensive study of: (1) attenuation of pressure transmitted through an unsaturated silt containing a trace of clay, (2) the effect of surface peak overpressure on the pressure transmitted through such a soil, (3) the effect of structure flexibility on the loading on structures buried in such a soil, and (4) the relationship between horizontal and vertical pressures on structures buried in such a soil (Reference 1). The relative success of Plumbbob Project 1.7 made it desirable to run similar tests in a different type of soil deposit when the opportunity occurred.

The study of pressures in soil below the water table is of particular importance in the design of underground structures because, at the depth of burial required for protection, it is likely that structures will extend below the water table. It is also possible that structures will be buried in soil deposits that are saturated up to the ground surface. For the above-mentioned reasons the present project was undertaken to study pressures in a sand deposit under two conditions: (1) with the water table at the surface, and (2) with the water table a few feet below the surface. The project was later limited because of financial considerations to the case in which the water table was a few feet below the ground surface.

1.3 PHILOSOPHY OF TEST PROGRAM

The field test program included 43 devices, each of which consisted of a rigid cylinder having one rigid end and one deformable diaphragm end. These devices were the same ones used by Operation Plumbbob Project 1.7 but were modified by having one deformable diaphragm end replaced by a heavy steel plate. The chief advantage of these devices is that they are much less costly than larger models or prototype structures. This made possible the use of a large number of them, thus giving the project maximum scope for a reasonable amount of money.

The use of such a drumlike device allows changing the overall flexibility of the device by changing the thickness of the end diaphragm. Because of this, the effect of varying the flexibility of the structure can be studied very simply by using diaphragms of different thicknesses on drums at the same location.

Another advantage of the drum device is that it readily lends itself to simple instrumentation. Because all the appreciable deformations of the device occur in the diaphragm, measurements of deflection or strain on the diaphragm can be compared with calibration test data to determine the pressure which produced these deformations. Furthermore, most of the necessary measurements could be of permanent rather than transient deformations, thus minimizing the need for costly electronic instrumentation.

The drums were buried at depths ranging from 0 to 20 feet at one location for each of two shots. These locations were chosen to give ground surface overpressures of approximately 250 psi from these two shots, which had predicted yields of 16 kt and 1.4 Mt, respectively. This range in yield should give sufficient difference in positive-phase duration to definitely establish any dependence of the pressure-transmission phenomena on positive-phase duration, at least for this type of soil deposit.

Attenuation with depth of pressure can be studied by placing identical drums at different depths. Similarly, by placing identical drums at the same depths but with different orientations, the effects of orientation can be studied.

1.4 THEORETICAL CONSIDERATIONS

No completely adequate theory has been developed for the transmission of air-induced pressure through soil. Some theories consider the soil to be an ideal elastic or ideal plastic material; however, the limitations imposed by these theories have generally made them too restrictive to be of much practical use.

In a saturated soil deposit under short-duration loading (or where large areas are loaded), it is usually assumed that the applied pressure is carried by the pore water, which is far less compressible than the soil skeleton. In order for any load to be carried by the soil skeleton, there must be flow of the pore water through the voids. Since no significant flow can occur in most cases of blast loading because the applied pressure pulse is of relatively short duration, the applied pressure is transmitted essentially as pore-water pressure. The state of stress in the soil deposit must be essentially hydrostatic in such a case.

A somewhat different situation exists when there is an upper layer of unsaturated soil such as exists in a sand deposit in which the water table is somewhat below the ground surface. In this case a blast pressure imposed on the surface of the soil deposit is transmitted to the level of the water table almost entirely by intergranular stresses. Therefore, it is reasonable to assume that the soil skeleton will continue to carry part of the pressure for some distance below the water table. The division of pressure between water and soil skeleton is unknown for the dynamic case.

If the pressure were applied statically over a limited area, little if any pore-water pressure would be produced, because the water would be free to move horizontally. If the static pressure were applied over a large area, there would still be negligible pore-water pressure if the soil skeleton remained porous enough to allow free relative movement of the pore water and the soil skeleton in the vertical direction. However, if the skeleton were compressed until it was essentially impervious, large pore-water pressures could be produced. Although this is un-

likely in the static case, it is possible where the load is rapidly applied. In this case, the inertial resistance of the water, together with the reduction in voids because of compression of the soil skeleton, considerably reduces the freedom of relative vertical movement of the soil skeleton and the pore water. The pressures produced in the pore water in this way can become very large and could result in the pressure being carried entirely by the pore water at some distance below the water table.

A structure buried in an unsaturated soil changes the stress state in the soil adjacent to the structure from that which would exist if the structure were not present. The amount of this change depends on the nature and extent of the differences in properties of soil and structure. One of the most important factors on which this change depends is the relative stiffness or compressibility of the soil and structure. The mechanism by which the pressure on a buried structure is changed by the deformation of the structure is often termed "arching." If the structure were stiffer (less compressible) than the soil mass replaced by it, the pressure on the structure would be greater than that which would exist in the soil if the structure were not present. Conversely, the pressure on a more compressible structure would be less than that in the soil if the structure were not present. One theory of the effect of relative compressibility of soil and structure upon the pressures acting on a buried structure has been developed in Reference 1.

When the structure is located below the water table, the problem is more complicated. If the soil-water mixture could be considered as a homogeneous material, its compressibility characteristics could be determined and the above theory applied to determine the pressures that would act on the buried structure. Unfortunately, there is little justification for this simplifying assumption. When the structure deflects away from the soil, arching may occur in the soil skeleton, thereby reducing the pressure exerted on the structure by the soil. Under this condition, however, water will flow through the voids and the determination of the pressure exerted by the water on the structure becomes a problem in hydraulic flow.

In order to solve this hydraulic-flow problem, it is necessary to have a certain amount of information about the soil, particularly its permeability. This information can only be obtained from an extensive series of tests, beyond the scope of this project.

No new theories will be presented here. On the contrary the results of this test will be used to determine if any new theory is needed or whether it can be assumed that the dynamic pressure acting on a structure below the water table is equal to that acting at the level of the water table. The theory presented by Reference 1 will be compared with the results obtained from drums above the water table.

Chapter 2

PROCEDURE

2.1 SHOT PARTICIPATION

The project participated during Shots Koa and Cactus detonated on Sites Gene and Yvonne, respectively, of the Eniwetok Proving Ground (EPG).

2.2 TEST DEVICES

Figure 2.1 shows the construction of the test devices (drums). Each consisted of a rigid steel cylinder 2 feet in diameter and 2 feet long with a heavy steel plate welded to one end, and a diaphragm, held in place by a clamping ring and bolts, at the other end. Originally, the drums had diaphragms on both ends, but during Operation Plumbbob the protruding clamping ring and bolts for the bottom diaphragm were found to make placement difficult. Placing the drums underwater for the Hardtack test would have been even more difficult; therefore, a steel plate was welded to one end of each drum to provide a flat surface for seating. In order to be consistent, no exception was made for the drums that were to have a horizontal orientation, although there was no problem of seating these drums.

Because many of the drums were to be placed in water and because all would be exposed to high humidity, it was necessary to completely seal each of the drums. This was accomplished by placing a neoprene gasket between the inner clamping ring and the diaphragm and by placing O-rings in grooves (in this same clamping ring) around each of the bolts. To determine whether the drums were adequately sealed, each was subjected to a preload external gas pressure of about 10 psi for several hours and checked for leakage. The pressure was then increased to 15 psi and released in order that all drums would have the same preload pressure; this also eliminated initial irregularities in the diaphragms. A pressure of 15 psi was chosen because this was the predicted maximum dead-load pressure on any of the diaphragms; preloading all drums to this pressure insured the absence of further deflections before the test.

Because the drums had aluminum diaphragms in contact with steel clamping rings in the presence of salt water, two coats of neoprene-base paint were applied to the diaphragm end of each drum in order to prevent corrosion.

A complete discussion of the reasons for the original choice of size, shape, and other characteristics of the test device can be found in Reference 1; only a brief summary will be given here.

A small structural model was chosen so that a large number of them could be used within the budget limitations. If the model were too small, however, it might not be possible for information obtained to be applied directly to the design of full-scale structures. The 2- by 2-foot drum was chosen as being large enough to represent a structure and small enough to be economical. The drum shape was chosen because it is easily fabricated and its compressibility characteristics can be changed simply by varying the thickness of the end diaphragm.

Three thicknesses of diaphragm were used, namely, 0.063, 0.125, and 0.50 inch. The number and choice of thicknesses were based on experience gained during Operation Plumbbob.

The 0.063-inch thickness was chosen to give probable failures under the blast loading. The failure pressure for a diaphragm of this thickness is about 200 psi whereas the surface peak overpressure was expected to be 250 psi. Failure of 0.063-inch diaphragms at all depths would indicate a lack of attenuation of the air-induced pressure with depth.

The 0.125-inch thickness was chosen to give a diaphragm thick enough not to fail under the predicted loads, yet thin enough to have large permanent deformations under these loads.

The 0.50-inch thickness was chosen to give a diaphragm stiffness great enough to make the overall drum compressibility less than that of the soil.

2.3 TEST LAYOUT

The two drum locations were chosen to give the same nominal peak ground-surface overpressure (250 psi) from each of two shots, one having a predicted yield of 16 kt and one of 1.4 Mt. The layout of the drums in each trench and the orientation of each trench with respect to ground zero for Shots Koa and Cactus are shown in Figures 2.2 and 2.3, respectively.

For Shot Koa, the scarcity of land area made it necessary to orient the trench so that the long axis was directed toward ground zero. This gave a variation in range for the 20 drums used for this shot of from 2,917 to 3,019 feet. For this large a shot, this variation in range was expected to give only a 30-psi difference in overpressure over the length of the tranch which would not cause any major difficulty in evaluating the test data.

For Shot Cactus, the long axis of the trench was perpendicular to a radial line through ground zero, thereby placing all the drums at approximately the same range of 600 feet.

The same number, type, and arrangement of vertical drums was used for each shot. Three vertical drums, each having a different diaphragm thickness, were included at each depth. The level of the tops of the diaphragms were at depths of 0, 2, 5, 8, 13, and 20 feet. The choice of diaphragm depths of 2, 5, and 8 feet was made to insure having at least one set of diaphragms near the level of the water table, which varied between depths of 3 feet and 8 feet. Depths of 0, 13, and 20 feet were chosen to complete the desired spread in depth of from 0 to 20 feet. Horizontal drums having 0.50-inch diaphragms were included at depths of 6 and 14 feet for Shot Koa and 6, 9, and 14 feet for Shot Cactus. In addition, a horizontal drum with a 0.125-inch diaphragm and one with a 0.063-inch diaphragm were included at depths of 1 and 3 feet, respectively, for Shot Cactus. All horizontal drums were so oriented that the diaphragms faced ground zero.

For the purposes of this test, it was necessary that the drums be placed in a soil deposit that provided uniform material in the influence area of the drums. The area of influence for each drum was defined by a 45-degree cone drawn from the center of the drum upward to the ground surface. Computations based on Boussinesq's equations (Reference 2) indicated that this would insure that the air-induced pressures transmitted to the drums would be transmitted almost entirely through the uniform material.

The drums were so arranged that no drum at a lesser depth lay within the influence cone of any drum at greater depth. The critical nature of the placement of the self-recording surface-pressure-versus-time gages made it necessary to place these within the influence area of some of the deeper drums. The spacing of the drums at any depth was great enough that the deflection of the diaphragm of one drum would have no effect on that of the diaphragm of another drum.

2.4 INSTRUMENTATION

This project was planned so that the minimum amount of data necessary for its success could be obtained from measurements of permanent deflection on the 0.063- and 0.125-inch diaphragms, and measurements of maximum deflection on the 0.50-inch diaphragms. To provide more complete data, transient strain was measured on the 0.50-inch diaphragms, and pressure was measured at the ground surface by means of pressure-versus-time gages furnished by the Ballistic Research Laboratories (BRL).

2.4.1 Deflection Measurements. Deflection was measured on the 0.063- and 0.125-inch diaphragms before the drums were buried and after they were recovered. These measurements were made by means of a frame which was supported on the clamping ring and held dial gages,

which measured offset at the center and quarter points on two perpendicular diameters. Dial gages are incapable of measuring with sufficient accuracy the small deflections of the 0.50-inch diaphragms; therefore, a scratch gage was developed to measure the center deflection of these diaphragms.

This gage consisted of: (1) a cylindrical brass rod that screwed into a threaded hole in the center of the diaphragm, and (2) a phonograph needle attached to a sleeve through which the cylindrical rod moved. The sleeve part of the gage was attached to a rigid bar mounted across the drum 6 inches below the diaphragm. The rod part of the gage was designed so that it could be removed easily without dismantling the drum. The deflection of the diaphragm would cause a longitudinal scratch to be produced on the brass rod by the phonograph needle, from which the amount of deflection could be determined. Inserting and removing the rod would put spiral scratches on the cylinder, which would show the zero-deflection position as well as the permanent deflection position. The use of a microscope in reading these scratches makes possible a high degree of accuracy in deflection measurement.

2.4.2 Strain Measurements. Deflection measurements could be made only before the drums were placed and after they were recovered. This was a serious disadvantage, because no indication could be obtained of the condition of the diaphragms after backfilling. There was also a chance that damage to the diaphragms during recovery would result in the loss of much valuable information. For these reasons, static strain was measured by means of SR-4 paper strain gages mounted on each diaphragm. The strain-gage readings would give an indication of the condition of the diaphragm at any time before the test. After the test but before recovery of the drums, static-strain measurements would give the condition of all diaphragms that had deflections of about 1 inch or less.

The deflections and strains of most of the 0.063- and 0.125-inch diaphragms were expected to be large. Standard SR-4 paper strain gages have a limited range, so post-yield gages were used on these diaphragms. The post-yield gages were basically the same as the standard gages used on the 0.50-inch diaphragms, except that they were capable of measuring strains of 8 to 10 percent (compared with about 1.5 percent for the standard paper gages). It was discovered during the calibration tests that the post-yield gages used were not reliable beyond 1.5 percent strain, for unknown reasons; however, it was then too late to correct the situation.

For measurement of static strain, two gages were placed along a diameter of each diaphragm, the center of each gage length being 1¼ inches from the center of the diaphragm. This placement was used for both the field-test and calibration-test diaphragms, so that the calibration-test results could be used directly in determining the pressures on the field-test diaphragms.

A standard dummy block arrangement was mounted in each drum to complete the electrical bridge. Cables were run from the strain bridges through the wall of each drum and out to terminal boxes at the end of the excavation. Static-strain readings were made, using a modified Foxborough portable strain indicator connected to the bridge circuit at the terminal box.

Dynamic strain was measured on all of the 0.50-inch diaphragms. The gages were of the same type as those used for the static-strain measurements on diaphragms of this thickness. The dynamic circuits differed from the static circuits only in being protected against electric arcing caused by the electromagnetic pulse at zero time. This protection was provided in the dynamic circuits because, unlike the static circuits, they could not be grounded at the drum and, also, because they had longer cables, which increased the possibility of having large differences of potential between the gages and ground.

The dynamic-strain gages were mounted along a diameter perpendicular to that on which the static gages were installed with the center of each gage length 1¼ inches from the center of the diaphragm. Seventeen channels of electronic equipment were used to record these measurements. The records obtained from this instrumentation gave a strain-versus-time history for each 0.50-inch diaphragm and provided a check on the pressures determined from the scratch-gage records.

2.4.3 Additional Measurements. The possibility of salt water leaking into the drums necessitated, in addition to the waterproofing of all the circuits within the drum, the installation of a water-depth gage in each drum to indicate how much water had leaked into the drum before the shot, because water in the drum could hinder the deflection of the diaphragm. These gages consisted of waterproofed resistors connected in series. Contacts were provided that would short out successive resistors as the water rose in the drum. The shorting of each resistor would cause a change in the overall resistance of the depth gage, which could be measured to determine the last submerged contact. In this way the water level would be known to within 3 inches, the distance between contacts.

To determine the magnitude and shape of the ground-surface pressure pulse, seven BRL self-recording pressure-versus-time gages were used, four for Shot Koa and three for Shot Cactus, as shown in Figures 2.2 and 2.3, respectively. At each location, a self-recording tide gage was installed to measure the level of the water table at the time of the shot. These gages were developed especially for this project.

2.5 FIELD OPERATIONS

The placement of the drums was accomplished by the excavating of two trenches and backfilling with beach sand around the drums as they were placed. The backfill below the water table was simply poured in, with no attempt at compaction. The sand above the water table was compacted by the repeated wetting of the ground surface. Density measurements made at depths of 1 foot and 2 feet showed an average dry density of 84 lb/ft^3 at a water content of about 13 percent. Diaphragm strains, as well as the amount of water leakage into the drums, were measured at frequent intervals throughout the operation.

The natural soil at both locations consisted of loose sand containing layers of cemented material. At the location for Shot Cactus, the first layer of cemented material occurred at a depth of about 6 feet; whereas at the location for Shot Koa, the first layer of cemented material was encountered at a depth of about 9 feet. Alternating layers of loose sand and cemented material were found below the levels of each of these first cemented layers. Because it was necessary to excavate to a depth of more than 22 feet, much cemented material had to be removed by blasting. This blasting caused the excavations to be irregular and considerably larger than the minimum specified dimensions.

Some difficulty was encountered in placing drums below the water table. Two factors were mainly responsible for this difficulty: (1) The drums were not bottom-heavy enough to resist tilting as fill was placed around them. (2) At the location for Shot Koa, the bottom of the excavation was covered with about 3 feet of a very fine material having the consistency of toothpaste, which did not present a firm bearing for the drums.

In order to place the drums in their proper positions, all soft material was removed. The stability of the drums was increased by connecting the vertical drums in sets of three by means of a bar welded to their bottoms. Lead bricks were then attached to this bar. A saddle of lead bricks was used to keep each horizontal drum in place. Figure 2.4 is a photograph of a set of three vertical drums being lowered into position. The strongback across the tops of the drums was used to facilitate handling and was removed after the drums were in position.

Because of the difficulties encountered in placement, the final positions of a few of the drums differed from the planned positions. In no case was this change critical. The positions of all drums at the time of the test are those given in Figures 2.2 and 2.3.

2.6 LABORATORY TESTS

In order to interpret the field-test results, a comprehensive laboratory program was necessary to determine the pressure-versus-deflection and pressure-versus-strain relationships for the diaphragms as clamped in the drums. The program was originally designed on the assumption that the response of the diaphragms to the blast wave would be essentially static.

The response was considered to be static because the natural periods of vibration of the diaphragms were comparatively short with respect to the expected rise time of the pressure pulse. Provisions were made, however, for a limited number of dynamic tests in the laboratory to check the dynamic response of the diaphragms.

2.6.1 Static Diaphragm Tests. The basic device used for the static diaphragm tests was very similar to the one used in the laboratory tests described in Reference 1. It consisted of a field-test drum with the bottom removed and holes in the sides for access. The calibration test setup for this project differed from that for Operation Plumbbob Project 1.7 in the inclusion of O-rings around the bolts and a neoprene gasket between the inner clamping ring and the diaphragm. This was done to simulate the field-test drum as nearly as possible. On top of the drum was welded a chamber having a heavy steel top that could be removed for changing diaphragms. Compressed gas was forced into this chamber to deflect the diaphragm downward. Pressures, diaphragm strains, and diaphragm deflections were measured.

Deflections of the diaphragms were measured by means of dial gages. Small brass tabs were glued to the diaphragm and wires were strung between these tabs and the dial gages. Weights were attached to the dial gages to keep the wires taut. Figure 2.5 is a photograph of the static-calibration test setup.

Pressure was controlled manually from a closed room for the protection of personnel. Four pressure gages with ranges of from 0 to 30 psi, 0 to 100 psi, 0 to 300 psi, and 0 to 600 psi were used. A 35-mm camera, located near the test device but operated from the control room, was used to photograph the dial gages at predetermined intervals of pressure. Diaphragm strain-gage readings were made at the same time as each photograph was taken; in this way, corresponding values for pressure, strain, and deflection were obtained.

During each calibration test, the diaphragm was first subjected to a 15-psi preload to reproduce the effects of the preload given all the field test drums. Four diaphragms of each thickness were tested. Two were tested without being unloaded except when it was necessary to reset the dial gages. The other two were tested by being loaded to a given pressure then being unloaded and reloaded to the next higher pressure desired. The loading and unloading tests gave the relationships of pressure to permanent deflection and pressure to permanent strain. Comparison of the results of the tests run in this manner with those of tests run by applying continually increasing pressure without unloading shows no difference in the behavior of the diaphragms.

The results of the static calibration tests are given in Figures 2.6, 2.7, and 2.8. Each curve represents the results of four diaphragm tests except that for the 0.50-inch diaphragm which represents the results of five tests. Figures 2.6 and 2.7 show the pressure-versus-center deflection curves for the three thicknesses of diaphragm. The solid curve for each diaphragm thickness corresponds to the initial loading of the diaphragm and each point on the curve represents the deflection of the diaphragm while loaded with the indicated pressure. The dashed curves represent the permanent deflections; the deflection indicated by a point on one of these curves is that which existed after the indicated pressure was removed.

Figure 2.8 gives the pressure-versus-strain relationships for the three thicknesses of diaphragms. The solid curves represent the strains during initial loading whereas the dashed curves represent the permanent or unloaded strains.

It was necessary for reasons of personnel safety to use a somewhat different setup for the tests of the 0.50-inch diaphragms beyond 500 psi. The same clamping rings were used, however, and results obtained agreed very well with those obtained with the original setup for pressures less than 500 psi. Therefore, the results of the tests using the modified setup were used directly, together with the results from the original test setup, in determining the pressure-versus-deflection and pressure-versus-strain curves for the 0.50-inch diaphragms.

2.6.2 Coupon Tests. The diaphragms used for the laboratory tests were cut from the same sheets of aluminum as were the field-test diaphragms. In addition, coupons were cut from each sheet of aluminum and tested in tension to determine the properties of the material and the variation in these properties between sheets and for different orientations in the same sheet. There was good uniformity of stress-strain characteristics for each thickness of material and no appreciable difference in ductility between the specimens taken with the direction of rolling and those cut against the direction of rolling for the 0.063- and 0.125-inch material. Although the 0.50-inch coupons exhibited uniform stress-strain characteristics regardless of orientation, the coupons oriented with the direction of rolling showed 17 percent less elongation and 34 percent less reduction in area when tested statically in tension than did those oriented perpendicular to the direction of rolling. This is of little consequence, because the deformations of the diaphragms made of 0.50-inch material were small.

2.6.3 Vibration Tests. Vibration tests were conducted on one diaphragm of each thickness, using the same device to hold the diaphragm as was used for the static calibration tests. The procedure was the same as that described in Reference 1 for similar tests on diaphragms. An electric vibrator such as is used for nondestructive testing was mounted below and in contact with the diaphragm. An electric pickup coupled to an oscilloscope was used to find the resonant frequencies of the diaphragm, because the frequency of vibration of the vibrator was varied. Because a large number of such frequencies were found for most of the diaphragms, an attempt was made to identify the modes by establishing the nodal patterns. Sand grains were sprinkled on the diaphragms during vibration; these grains migrated to the nodal lines, which undergo no displacement during vibration. The sand patterns thus identified the nodes. Because of the small amount of data obtained from these tests, the results of the vibration studies of both projects are combined in Table 2.1. The slight differences in details of the test setup from that used in the earlier tests, such as the inclusion of O-rings around the bolts and a gasket over the lower clamping ring, apparently had little if any effect. In cases in which the same mode was obtained in both tests for a diaphragm of given thickness, the frequencies corresponding to this mode were in good agreement. Therefore, no distinction is made in Table 2.1 regarding the series of tests from which the particular frequency was obtained. Only the first (i.e., lowest) four modes of vibration are given in Table 2.1, because the higher modes are of far less importance.

Preloading the diaphragms before vibrating caused a decrease in the natural periods for the various modes. A 15-psi preload, such as was given all the field-test diaphragms in the present project, decreased the lowest-mode periods as follows: 0.50 inch, 2 msec before and after preload, no significant decrease; 0.25 inch, from 4 msec to 3 msec; 0.125 inch, from 8 msec to 3 msec; 0.08 inch, from 12 to less than 5 msec (5 msec for 10-psi preload—15-psi preload caused erratic behavior of the diaphragm); 0.063 inch, from 8 to 3 msec. The lowest mode of the 0.04-inch diaphragm was not determined, because of the erratic behavior of this diaphragm at lower frequencies; however, the third mode decreased from 6 to 2 msec after a preload of 10 psi. When a preload pressure greater than 15 psi was applied, it became impossible to excite the lowest mode in all but the thickest diaphragms. The reason for this undoubtedly is that the diaphragm was being forced into the shape of the first mode by the applied pressure, because the first mode corresponds to the static-deflection configuration. Because it is so difficult to excite vibrational response of the diaphragms in the lowest mode, and because this mode is the only one in which significant dynamic response would occur under the field-test conditions, the deflections of the diaphragms should be the same as would occur if the load were static.

2.6.4 Dynamic Tests. In addition to the vibration tests of the dynamic behavior of the diaphragms, tests were made of a few diaphragms under a dynamically applied gas pressure. To accomplish this, one of the large dynamic loading machines at the University of Illinois was

modified to permit applying a gas pressure over the entire area of the diaphragm. (The machine was originally designed to apply loads by means of a moving piston.) A transition chamber was built, which replaced the lid of the static-test setup, and on top of which the dynamic load machine could be attached. The dynamic load machine was used only as a large, quick-opening valve capable of passing a large volume of gas rapidly enough to obtain a rise time of less than 10 msec for the pressure pulse acting on the diaphragm.

A large number of tests were run; however, most of the effort in these tests was directed toward the development of suitable instrumentation rather than toward study of diaphragm behavior. The first group of tests checked the performance of the Consolidated Electrodynamics Corporation (CEC) pressure gages used to measure the applied pressure and the effect of the location of these gages. The records obtained from these gages showed that the pressure on the gage located in the wall of the chamber above the diaphragm was higher than that measured by the gage mounted in the center of the diaphragm (a 0.75-inch diaphragm was used for all the preliminary tests). In addition, these records showed high-frequency oscillations of the order of 28 to 30 kilocycles.

A thin, streamlined plate to which two of the CEC gages were attached was mounted across the chamber for comparison of pressure at this location in the chamber with that measured at the center of the diaphragm. Again there was poor agreement between the pressures measured at different locations, and again 30-kc oscillations appeared on all the records. For further comparisons, additional tests were run with strain gages mounted on the diaphragm, and also with a piezoelectric gage mounted in the center of the diaphragm. The records from the strain gages and those from the piezoelectric gage agreed fairly well with records from the CEC gage mounted in the diaphragm but not with records from CEC gages mounted elsewhere. The piezoelectric gage also showed much less high-frequency oscillation than did the CEC gage. This indicates that the 28- to 30-kc oscillations shown by the CEC gages were produced by the response of the gages to the applied pressure pulse. The records from the CEC gages and from the piezoelectric gage all show lower frequency oscillations. These oscillations were not caused by the dynamic response of the gages, but represent the variation of the pressure acting on the gages. The oscillations were caused by multiple shock fronts produced by reflections from the walls of the chamber. The magnitude and frequency of these oscillations are determined by the test-chamber geometry.

Tests were next run with all available gages mounted in the diaphragm to determine the distribution of pressure over the diaphragm surface. The pressure distribution was found to be nonuniform; the apparent cause was as before, the geometry of the test setup. For this reason, the results of the dynamic laboratory tests are not directly comparable with the static laboratory tests, although the differences should not be great.

A limited number of dynamic tests were run on these diaphragms, and the results of one such test are shown in Figure 2.9. This figure shows a comparison of pressure-versus-time replots as determined from records obtained from a pressure gage, strain gages, and a slide-wire deflection gage that was developed for these tests. Two significant phenomena are shown by this figure: (1) the record obtained from the deflection gage agrees fairly well with that from the piezoelectric pressure gage although the peak shown by the pressure-gage record is missing from the deflection-gage record; and (2) the two strain-gage records agree with one another but show peak pressures about 25 percent lower than do the deflection and pressure-gage records. These phenomena occurred in all such tests. No other results are presented here because the replots shown in Figure 2.9 are typical of the results of all the tests, and because uncertainties regarding the data prevent drawing conclusions from it at present.

Attachment of the slide-wire deflection gage and pressure gages to the diaphragm was unsatisfactory in that it changed both the static- and dynamic-deformation characteristics of the diaphragm. The change in deformation characteristics was caused not only by the holes put in the diaphragm to place the gages but also by the mass of the gages. The resistance to movement of the slide-wire gage had a particularly severe effect on the deformation characteristics of the thin diaphragms.

The unsatisfactory conditions caused by attaching the gages to the diaphragm could have been corrected by mounting the pressure gages on a plate just above the diaphragm, and using a different method of determining deflections. However, the oscillations caused by the multiple shock fronts could not be so easily eliminated nor could the nonuniformity of pressure distribution. Both of these effects were the result of test-chamber geometry and could only have been eliminated through extensive modification of the dynamic-test setup. Such modification was beyond the scope of this project; therefore, the dynamic tests were discontinued. (Subsequently, modification of the test-chamber geometry for a later project eliminated the oscillations caused by multiple shock fronts.)

2.7 DATA REQUIREMENTS

The primary data required from the field program included the permanent deflections of the two thinnest diaphragms and the transient deflections of the thickest diaphragms. Additional data required included the preshot and postshot permanent strains of the 0.063- and 0.125-inch diaphragms and the preshot strains and transient strains of the 0.50-inch diaphragms. The pressures on the field-test diaphragms were determined from these strain and deflection measurements, using the calibration curves of Figures 2.6, 2.7, and 2.8.

Measurements of surface air-blast pressure were included in this project, to check the values obtained from those drums having diaphragms at the surface and to complement the data obtained from these drums. A few soil-density tests were also included, and soil samples were obtained and shipped to the University of Illinois in order that further laboratory tests could be run if the field-test results made it advisable to have more information regarding the soil.

The level of the free-water table at each location at the time of the test was the final item of information required. To provide this, self-recording tide gages were developed and placed at each location.

TABLE 2.1 MEASURED AND THEORETICAL NATURAL PERIODS OF CLAMPED, UNLOADED DIAPHRAGMS

Mode	Nodal Pattern	Natural Period, msec											
		0.04		0.063		0.08		0.125		0.25		0.50	
		Meas	Theor	Meas	Theor	Meas	Theor	Meas	Theor	Meas	Theor	Meas	Theor
1		—	20	8	15	12	10	8	7	4	3	2	2
2		—	10	4	7	8	5	3	3	2	2	1	1
3		6	6	4	4	4	3	2	2	1	1	—	—
4		4	5	3	4	3	3	2	2	1	1	—	—

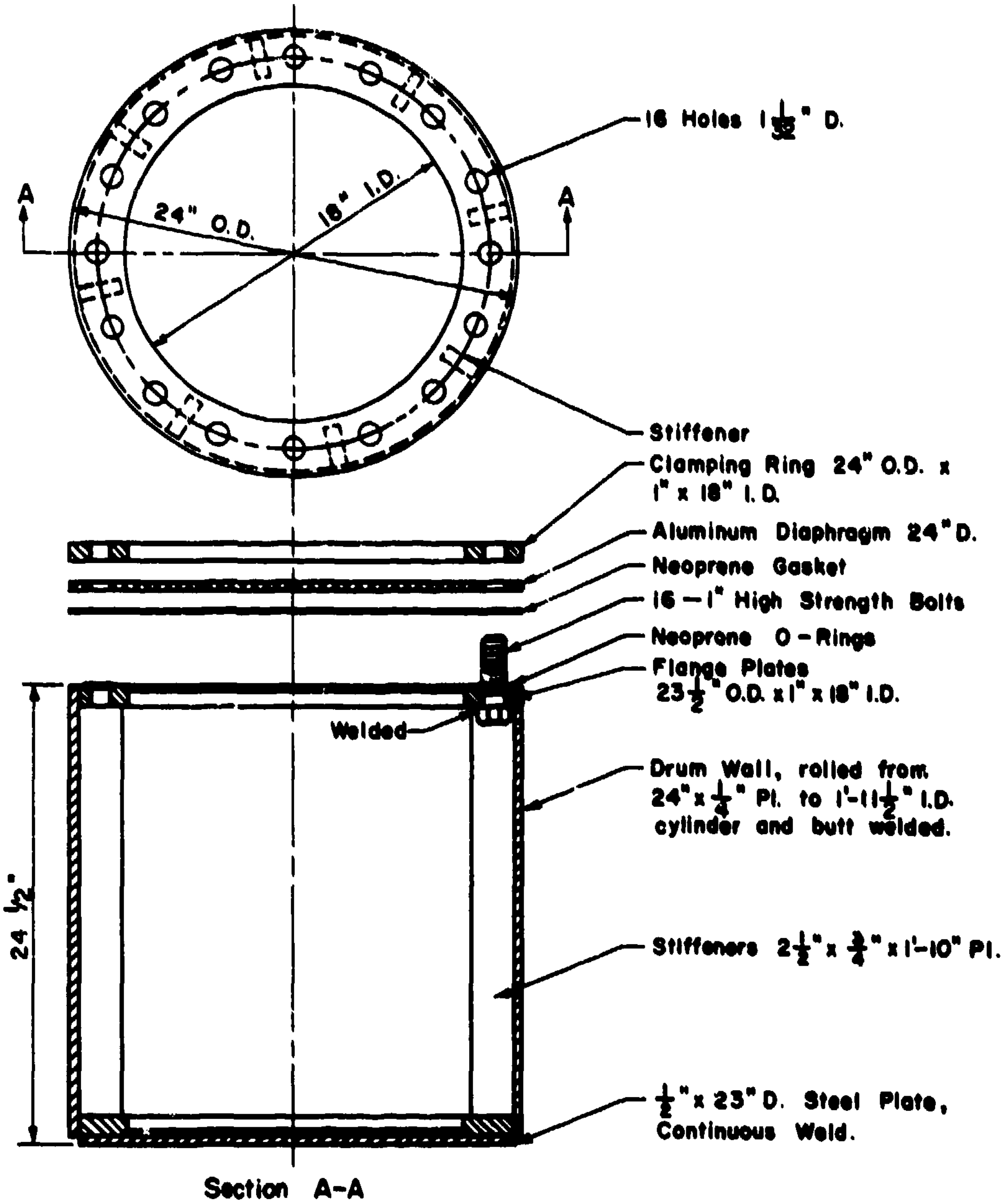

Figure 2.1 Plan and section of test device.

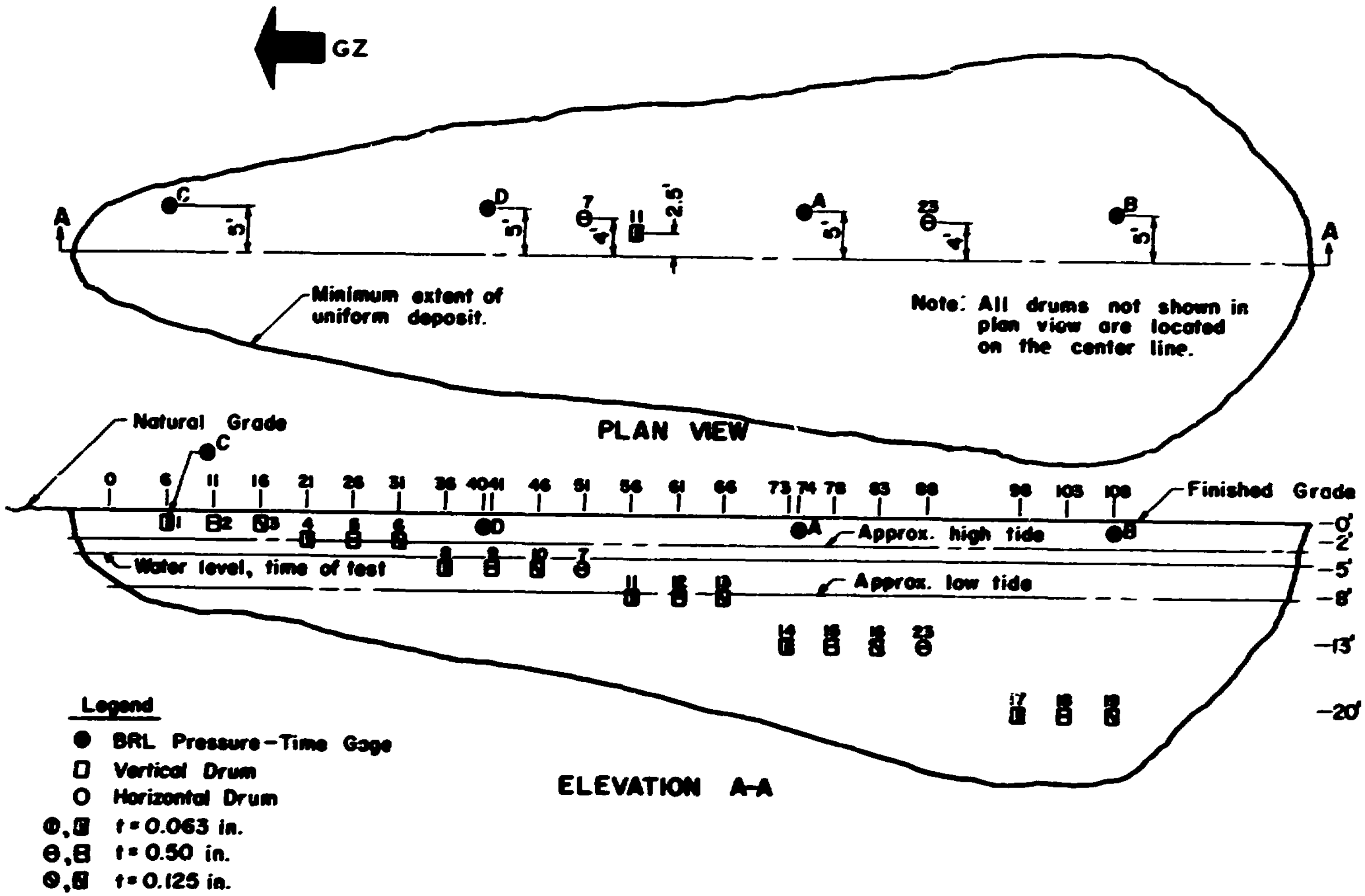

Figure 2.2 Drum Layout for Shot Koa.

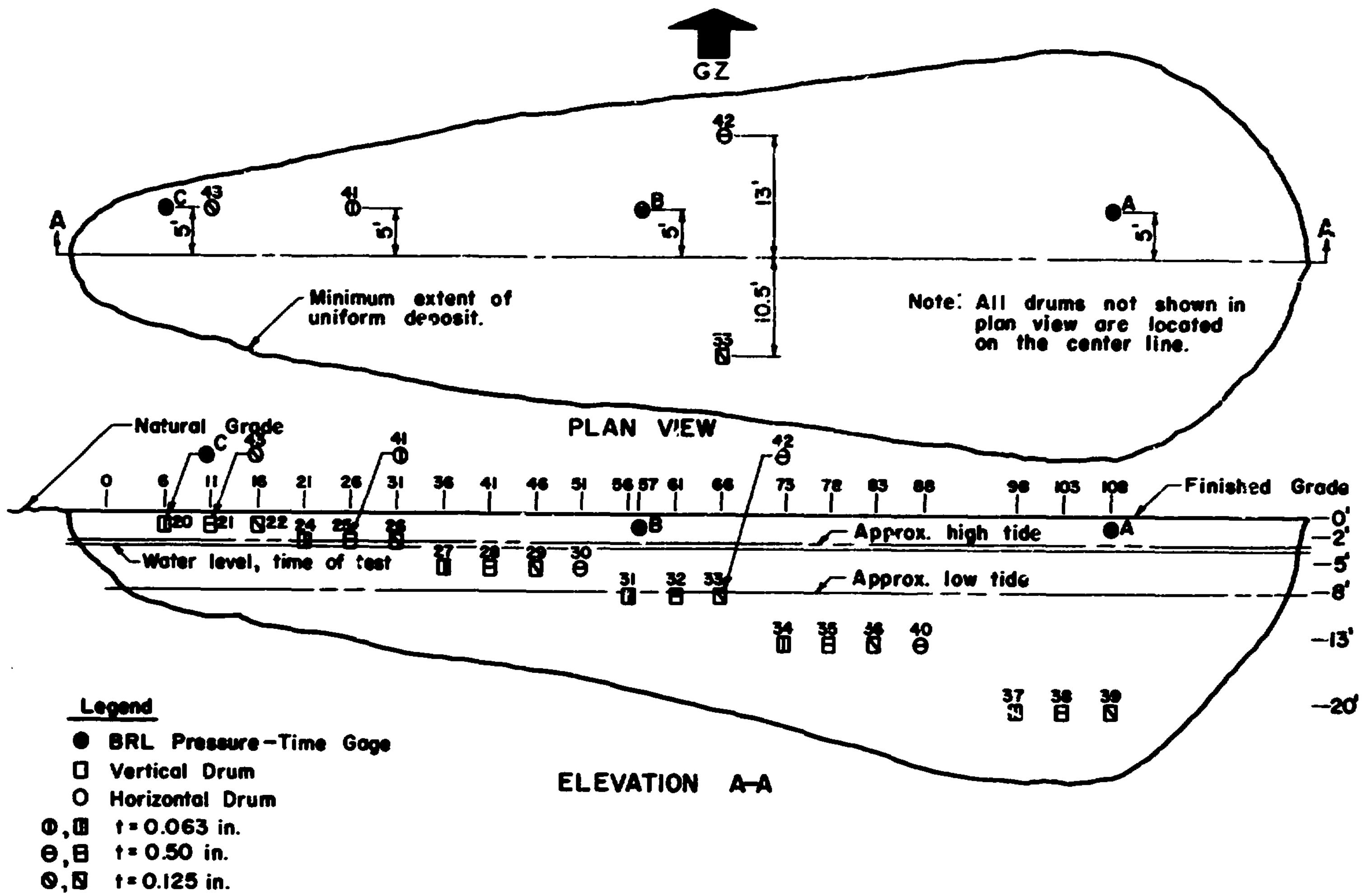

Figure 2.3 Drum layout for Shot Cactus.

Figure 2.4 Placing the vertical drums.

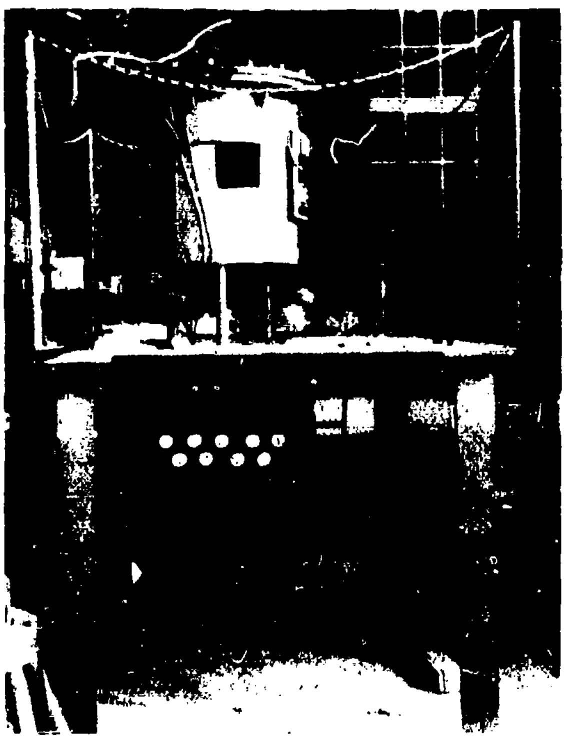

Figure 2.5 Laboratory calibration setup.

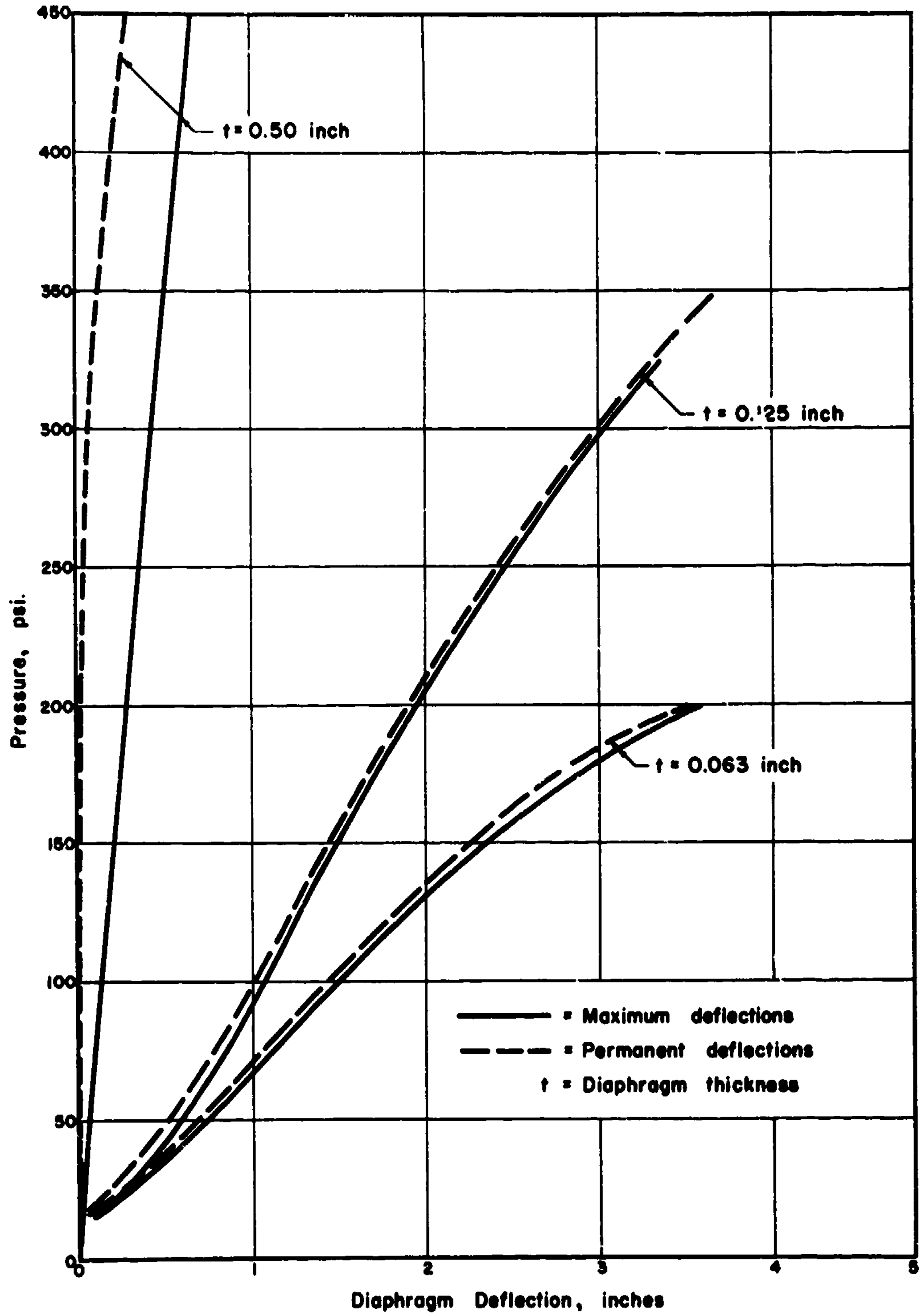

Figure 2.6 Diaphragm calibration curves for deflections.

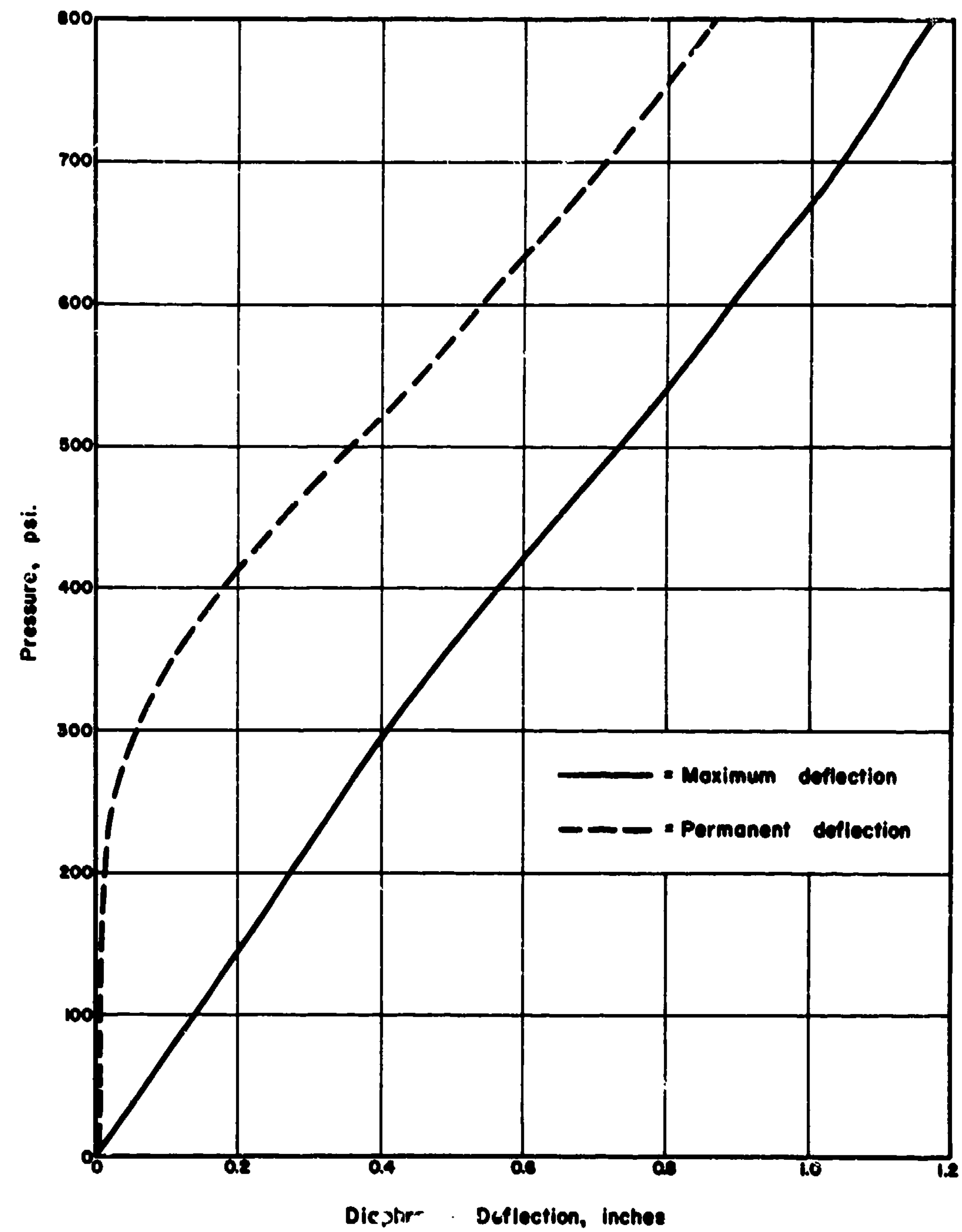

Figure 2.7 Extended 0.50-inch diaphragm calibration curves for deflections.

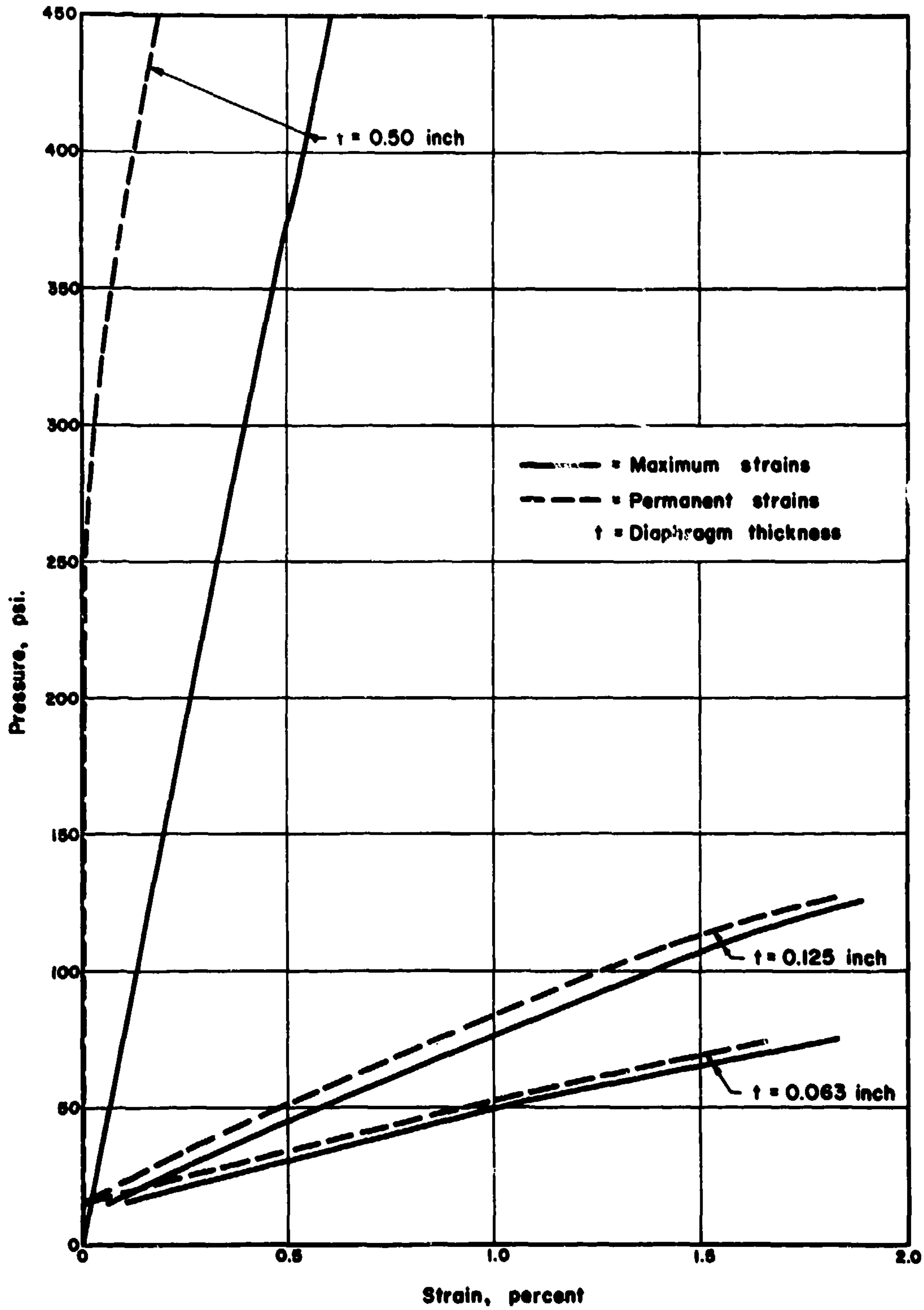

Figure 2.8 Diaphragm calibration curves for strains.

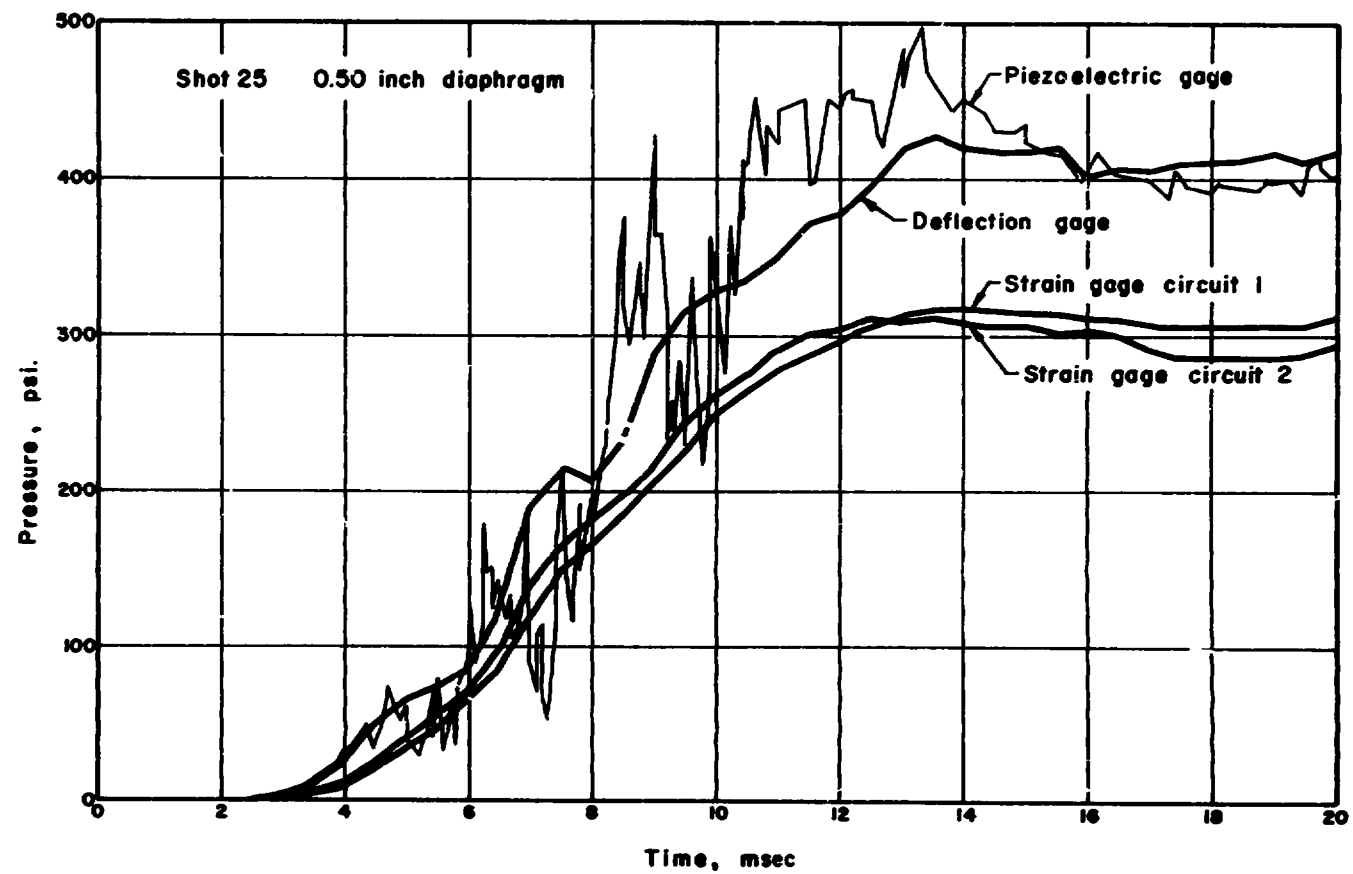

Figure 2.9 Typical pressure-versus-time replots from laboratory dynamic tests of diaphragms.

Chapter 3

RESULTS

3.1 SHOT KOA

3.1.1 Surface Peak Overpressure. Readable records were obtained from three of the four BRL self-recording pressure-versus-time gages. Two of the three readable records were considered questionable by BRL when final interpretation was made; the third record showed a baseline shift. Replots of these records are shown in Figures 3.1, 3.2 and 3.3, and a summary of the measured pressures is given in Table 3.1. Because there was a difference of about 100 feet in the ground ranges of the BRL gages at opposite ends of the trench, the measured pressures are not directly comparable. The measured surface peak overpressure varied from 288 psi at the location of the nearest drum to 260 psi at the location of the drum farthest from ground zero. The 28-psi difference in gage readings is approximately equal to the difference in peak surface overpressure associated with the difference between the ground ranges of these gages.

No serious error would be introduced by assuming the pressure to be a constant value, equal to the average of the pressures measured by the three gages, over the entire length of the trench. This average value would be 278 psi if measured peak values are considered, and 240 psi of the BRL-determined pressures are used.

The BRL-determined pressures are estimates of the highest real pressures, i.e., indicated pressures corrected for overshoot. These estimates were made by examining simultaneously the records from all gages used for this shot in order to identify and disregard spurious oscillations. This simultaneous examination also served to identify any record that was questionable because the shape of the record did not fit the pattern of the majority of the records. The apparent discrepancy in the record (the replot of which is shown in Figure 3.1) is that the indicated pressure did not approach zero for times greater than 200 msec as did the other records for Shot Koa. In Figure 3.2 it can be seen that there were unusual oscillations following the first peak.

3.1.2 Free-Water Level. The free-water level in the trench for Shot Koa was 4.5 feet below the ground surface; therefore, the vertical drums at depths of 0 and 2 feet were above the water table, whereas the vertical drums at depths of 5, 8, 13, and 20 feet were below the water table. The horizontal drums, which were at depths of 6 and 14 feet, were completely below the water table.

3.1.3 Diaphragm Pressures. Only one transient strain-gage record, that from the surface 0.50-inch diaphragm, was obtained because all other records were destroyed during recovery. The pressure-versus-time replot of this record is shown in Figure 3.4. This replot indicates a possible overshoot on the first peak, which would mean the peak value of 318 psi is probably too high. The scratch gage on the same diaphragm indicated 295 psi, and the BRL pressure-versus-time gage at the same location (Gage C) showed 288 psi. The shape of the BRL gage record is very similar to that of the replot of the 0.50-inch diaphragm record. The permanent deflection of the nearby 0.125-inch diaphragm indicated 270 psi.

All replots presented in this report were made using the pressure-versus-loaded strain curves of Figure 2.8 together with the strain-versus-time records. In addition, it was neces-

sary to determine the pressure-versus-strain relationships in regions in which the strain was less than the previous maximum strain. It was found that in such regions the pressure-versus-strain relationship was a straight line, the slope of which varies with the maximum strain previous to unloading. The variation of the slope of this straight-line relationship was plotted against previous maximum pressure for each thickness of diaphragm. The slope corresponding to any previous maximum pressure could then be easily found from these curves and, by use of this slope together with the previous maximum pressure, the pressure corresponding to any strain less than the previous maximum strain could be found readily. A fuller explanation of this method, together with typical recovery-slope versus previous maximum-pressure curves, is given in Reference 1.

Table 3.2 summarizes the measured deflections of all the diaphragms. The pressures determined from these deflections by using the calibration curves of Figures 2.6 and 2.7 are summarized in Table 3.3. Also included for comparison is the pressure on the surface 0.50-inch diaphragm as determined from the transient-strain record.

No values of permanent strains or the pressures determined from them are given. Most of the gages on the 0.063-and 0.125-inch diaphragms failed because the strains produced were beyond their allowable range. The few gages that were not over-ranged yielded results that agreed with those obtained from permanent-deflection measurements, although some of the permanent strain measurements were uncertain because of shorting to ground. It was considered unnecessary to present both permanent and transient strain values for the 0.50-inch diaphragms, because the permanent measurements were inherently less accurate. For the same reason, permanent deflection measurements on the 0.50-inch diaphragms (as obtained from the scratch gages) are not included. The pressures determined from these permanent deformations generally agree with those determined from transient deformations.

3.2 SHOT CACTUS

3.2.1 Surface Peak Overpressure. Usable records were obtained from all three BRL surface pressure gages; however, all are listed as questionable by BRL. Replots of these records are shown in Figures 3.5, 3.6, and 3.7; a summary of the peak pressures and BRL's interpretation of the highest real pressures is given in Table 3.4. The BRL-interpreted peak in each case agrees very well with the highest measured peak. There is a considerable spread in the pressures indicated by the three gages, which were all located at the same distance from ground zero. Gages B and C, which indicated peak pressures of 332 and 334 psi, respectively, agree not only in peak pressure, but also in general shape. The record from Gage A, which indicated a much lower peak pressure of 253 psi, shows the same general shape as shown by Gages B and C, except that Gage A indicated a far less abrupt increase of pressure to the first peak. This initial peak also appears to be somewhat cut off. Although there is no positive evidence that the lower pressure measured by Gage A is in error, these factors indicate a strong possibility that it is.

Gage C, which was situated very near the surface drums, showed a pressure of 334 psi, which is virtually the same as the pressure on the 0.125-inch diaphragm (337 psi) as determined from permanent deflections. Transient-strain and deflection measurements on the surface 0.50-inch diaphragm indicated a somewhat higher pressure—383 psi from deflections and 408 psi from strains. The strain record for this diaphragm, which is given in Figures 3.8, 3.9, 3.10, 3.11 and 3.12, shows that the first peak was not the highest pressure, whereas all three BRL gages show that the highest pressure occurred on the first peak. Moreover, the value of the first peak indicated by the 0.50-inch diaphragm was 335 psi, which coincides, within the precision of the measurements made, with the pressures indicated by the nearby 0.125-inch diaphragm and the BRL gage. This close agreement in first peaks, together with the fact that the maximum pressure shown by each of the BRL gages occurred on the first peak, indicates the possibility that the peak value of 408 psi indicated by the 0.50-inch diaphragm was in error.

3.2.2 Free-Water Level. The water table at the location for Shot Cactus was 3.6 feet below the ground surface. The diaphragms for the vertical drums at depths of 0 and 2 feet were above this level whereas all others were below. The water table was 0.4 feet above the bottom of the horizontal drum at a depth of 3 feet but, because of the 3-inch-wide clamping ring, only an extremely small area of the diaphragm was under water. The 1-foot-deep horizontal drum was completely above the water table and the 6-, 9-, and 14-foot-deep drums were completely below.

3.2.3 Diaphragm Pressures. No record was obtained from the transient-strain circuit of Drum 35, a vertical drum at a depth of 13 feet, because of a circuit failure prior to the test. All other circuits produced satisfactory records. Figures 3.8 through 3.12 show the pressure-versus-time replots of the records obtained from the vertical drums, and Figures 3.13 through 3.15 show replots for the horizontal drums. In Figures 3.8 through 3.12, the replots show a gradual decrease in peak pressure together with a rounding-off of the diaphragm-pressure pulse with increasing depth down to a depth of 8 feet. There was no record from the 13-foot drum, but the 20-foot-drum record indicated a peak pressure nearly three times as great as did the 8-foot-drum record. Furthermore, the peak pressure on the 20-foot-deep diaphragm exceeded the peak pressure on the diaphragm at a depth of 2 feet. There is another peculiarity in the pressure-versus-time curve from this 20-foot-deep diaphragm in that no decay of the pressure below about 250 psi is indicated. This is, of course, an impossibility; therefore, the record must be in error. Before the peak pressure shown by this record is discounted, however, it would be well to examine the deflection measurement results. These are given in Tables 3.5 and 3.6. Table 3.5 summarizes the measured deflections of all diaphragms, and Table 3.6 summarizes the pressures determined from these deflections using the pressure-versus-deflection curves of Figure 2.6. Also included in Table 3.6 for comparison is a summary of the peak pressures determined from the transient strain records.

The pressures on the 0.063- and 0.125-inch diaphragms as well as those on the 0.50-inch diaphragms can be seen to decrease as the depth increases to 8 feet. At a depth of 13 feet, all show an abrupt increase, with a further increase at 20 feet. The difference between the pressure on the 0.125-inch diaphragms at 13 feet and that at 20 feet is considerably greater than the differences for the 0.063- and 0.50-inch diaphragms. The fact that the deflection of the 0.125-inch diaphragm at this depth was greater than that of the 0.063-inch diaphragm is questionable, because the soil pressure should have been the same around both of these closely situated drums and, under this condition, the thinner diaphragm should deflect more. Furthermore, the pressure on this 20-foot-deep 0.125-inch diaphragm is greater than that on the 0.50-inch diaphragm at the same depth. This contradicts the idea that diaphragm pressure depends on diaphragm stiffness.

In view of the magnitudes of the pressures determined from deflection measurements on the diaphragms at depths of 12 and 20 feet, the pressure indicated by the transient-strain record from the 0.50-inch diaphragm at 20 feet cannot be disregarded. The sharp-rise portion of the pressure-versus-time replot of this record likewise cannot be discounted.

The records from the horizontal drums show an increase of diaphragm pressure with depth, together with an increasingly sharp-peaked pulse. The pressures determined from deflections substantiate the increase of horizontal pressure with depth. These measurements also tend to substantiate the increase in pressure with depth shown by the vertical drums.

TABLE 3.1 MEASURED SURFACE PEAK OVERPRESSURES, SHOT KOA

Gage Designation	Gage Position: Distance from End of Trench	Gage Position: Distance from Ground Zero	Indicated Surface Peak Overpressure: Max	Indicated Surface Peak Overpressure: BRL Max*	Comments
	ft	ft	psi	psi	
C	6	2,917	288	227	Questionable
D	40	2,951	285	250	Questionable
A	74	2,985	Record obliterated		Record obliterated
B	108	3,019	260	242	Baseline shift

* Corrected for overshoot.

TABLE 3.2 MEASURED DIAPHRAGM CENTER DEFLECTIONS, SHOT KOA

Drum Orientation	Drum Depth	Measured Diaphragm Deflections: 0.063 inch Permanent Deflection	0.125 inch Permanent Deflection	0.50 inch Transient Deflection
	ft	inch	inch	inch
Vertical	0	Failed	2.628	0.402
	2	1.081	1.000	0.409
	5	0.899	0.729	0.340
	8	Failed	2.564	1.004
	13	Failed	3.741	1.174
	20	Failed	2.636	0.538
Horizontal	6	—	—	0.360
	14	—	—	0.793

TABLE 3.3 DIAPHRAGM PRESSURES DETERMINED FROM MEASURED DIAPHRAGM DEFLECTIONS AND STRAINS, SHOT KOA

Drum Orientation	Drum Depth	Diaphragm Pressures: 0.063 inch Permanent Deflection	0.125 inch Permanent Deflection	0.50 inch Transient Deflection	0.50 inch Transient Strain
	ft	psi	psi	psi	psi
Vertical	0	>200	270	295	318
	2	76	100	301	—
	5	64	72	251	—
	8	>200	266	672	—
	13	>200	345	800	—
	20	>200	270	382	—
Horizontal	6	—	—	266	—
	14	—	—	536	—

TABLE 3.4 MEASURED SURFACE PEAK OVERPRESSURES, SHOT CACTUS

Gage Designation	Distance from End of Trench	Indicated Surface Peak Overpressure		Comments
		Maximum	BRL Maximum*	
	ft	psi	psi	
C	6	334	334	Questionable Record
B	57	332	325	Questionable Record
A	108	253	253	Questionable Record
		Average = 307	304	

* Corrected for overshoot.

TABLE 3.5 MEASURED DIAPHRAGM CENTER DEFLECTIONS, SHOT CACTUS

Drum Orientation	Drum Depth	Measured Diaphragm Deflections		
		0.063 inch Permanent Deflection	0.125 inch Permanent Deflection	0.50 inch Transient Deflection
	ft	inch	inch	inch
Vertical	0	Failed	3.451	0.533
	2	0.956	0.871	0.406
	5	1.090	0.900	0.345
	8	0.612	0.541	0.199
	13	2.275	1.369	0.333
	20	3.029	3.126	0.396
Horizontal	1	—	0.497	—
	3	0.472	—	—
	6	—	—	0.119
	9	—	—	0.212
	14	—	—	0.401

TABLE 3.6 DIAPHRAGM PRESSURES DETERMINED FROM MEASURED DIAPHRAGM DEFLECTIONS AND STRAINS, SHOT CACTUS

Drum Orientation	Drum Depth	Diaphragm Pressures			
		0.063 inch	0.125 inch	0.50 inch	
		Permanent Deflection	Permanent Deflection	Transient Deflection	Transient Strain
	ft	psi	psi	psi	psi
Vertical	0	>200	337	383	408
	2	68	85	203	273
	5	71	89	255	212
	8	45	53	145	109
	13	152	143	246	—
	20	182	312	292	310
Horizontal	1	—	49	—	—
	3	37	—	—	—
	6	—	—	86	61
	9	—	—	154	118
	14	—	—	295	243

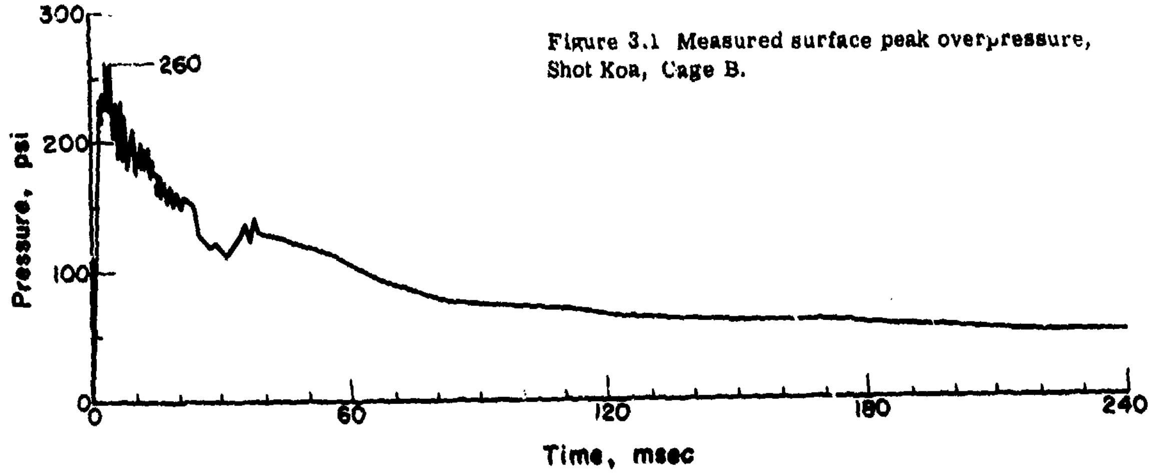

Figure 3.1 Measured surface peak overpressure, Shot Koa, Gage B.

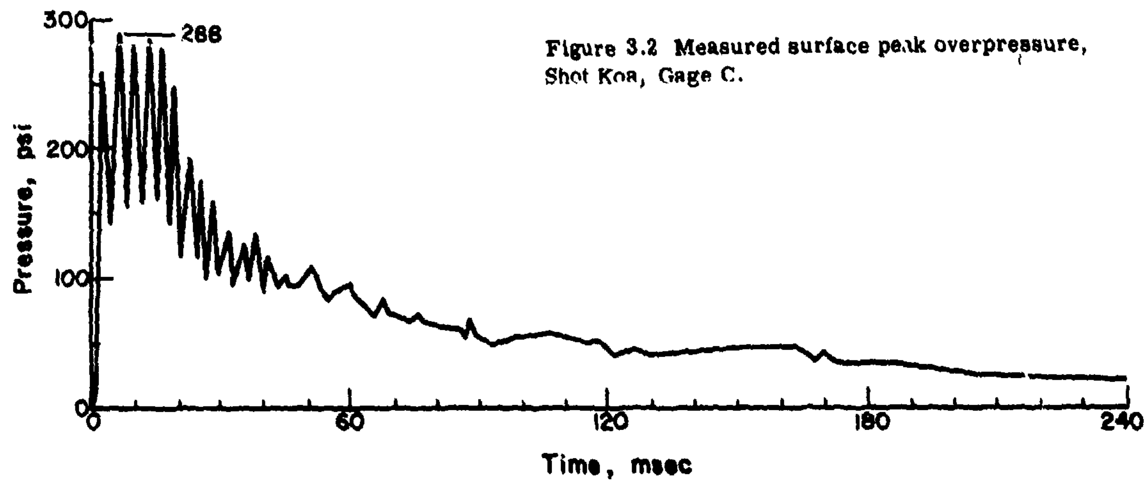

Figure 3.2 Measured surface peak overpressure, Shot Koa, Gage C.

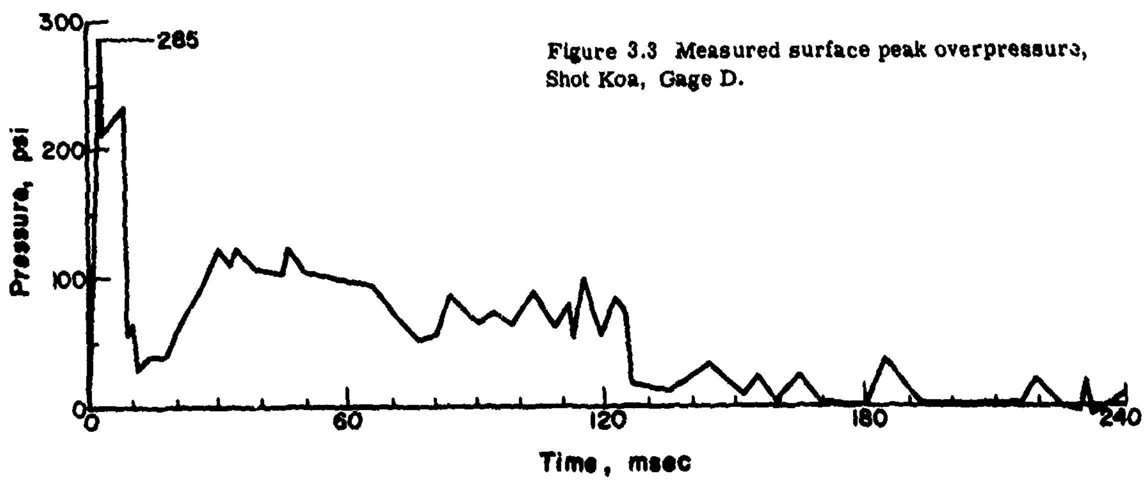

Figure 3.3 Measured surface peak overpressure, Shot Koa, Gage D.

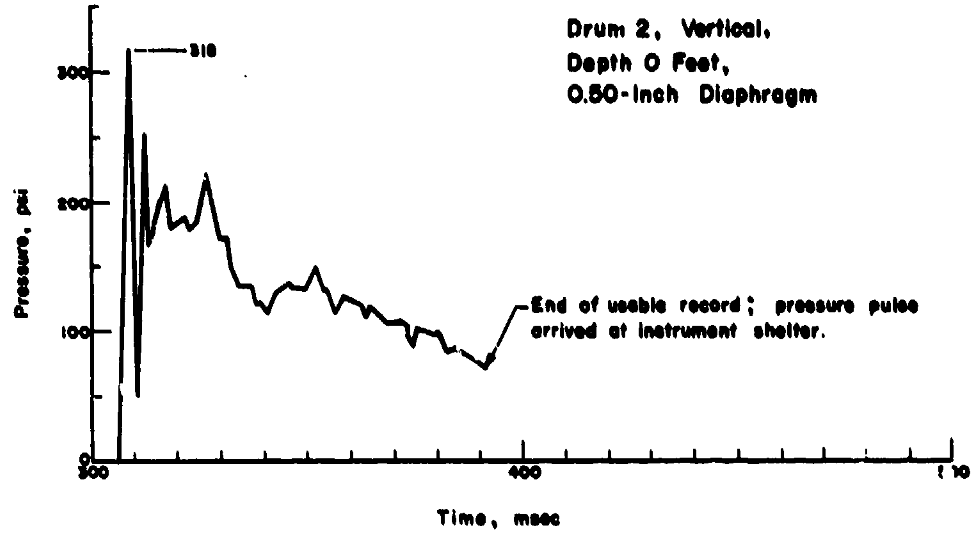

Figure 3.4 Diaphragm strain-gage pressure-versus-time replot, Shot Koa.

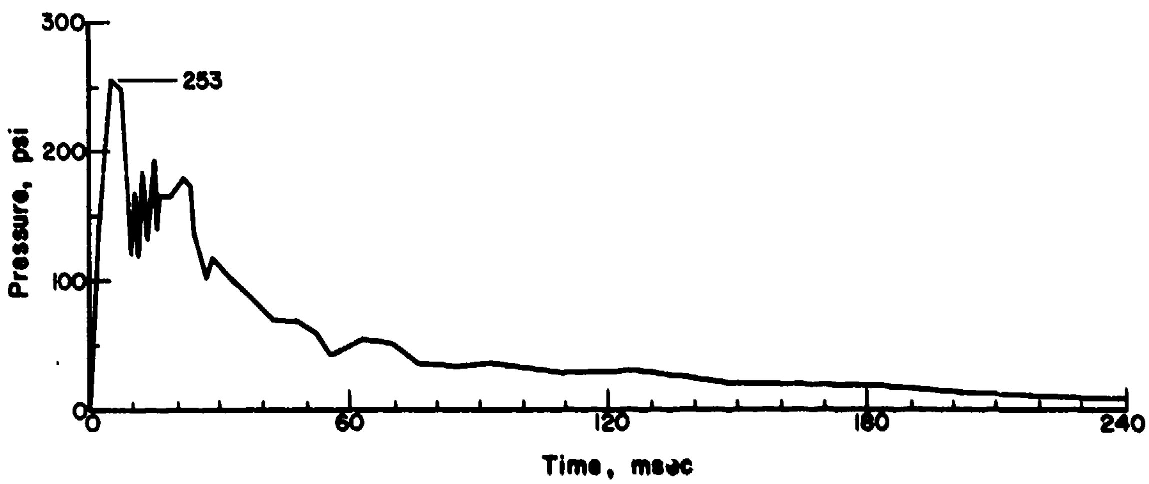

Figure 3.5 Measured surface peak overpressure, Shot Cactus, Gage A.

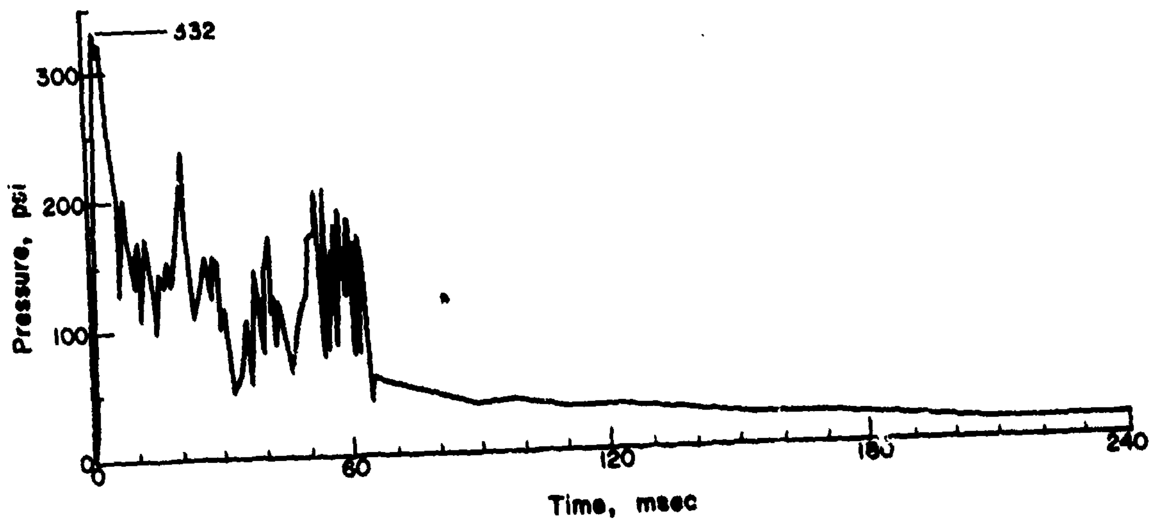

Figure 3.6 Measured surface peak overpressure, Shot Cactus, Gage B.

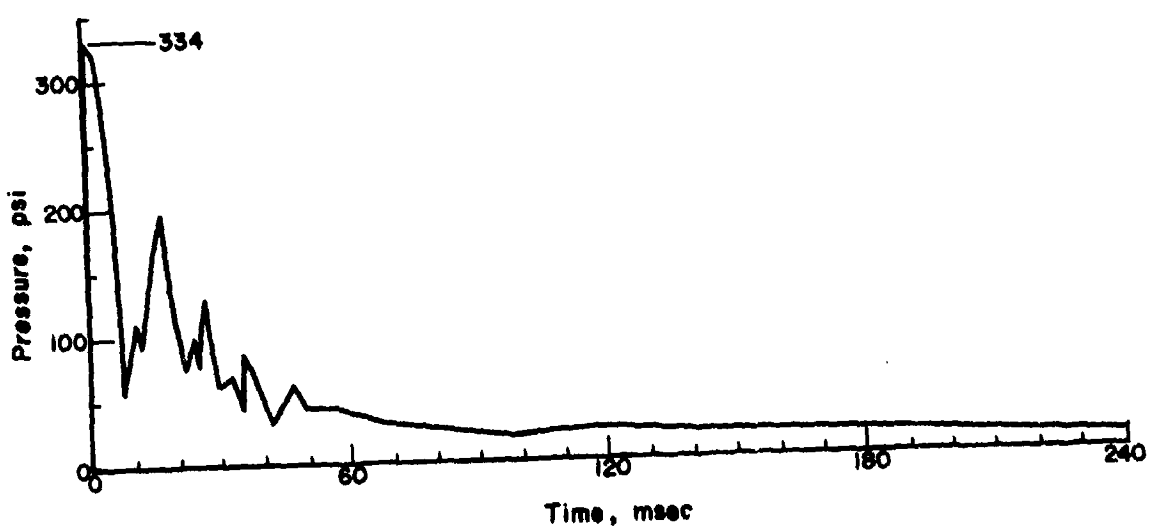

Figure 3.7 Measured surface peak overpressure, Shot Cactus, Gage C.

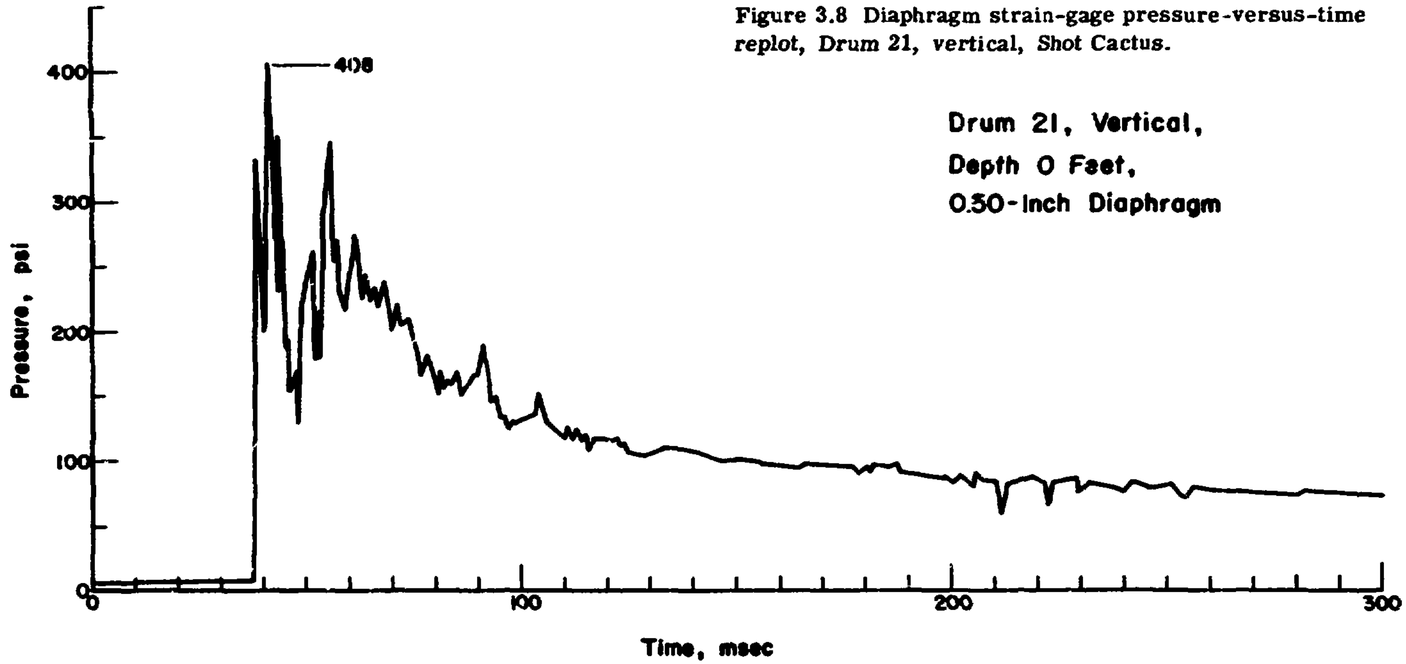

Figure 3.8 Diaphragm strain-gage pressure-versus-time replot, Drum 21, vertical, Shot Cactus.

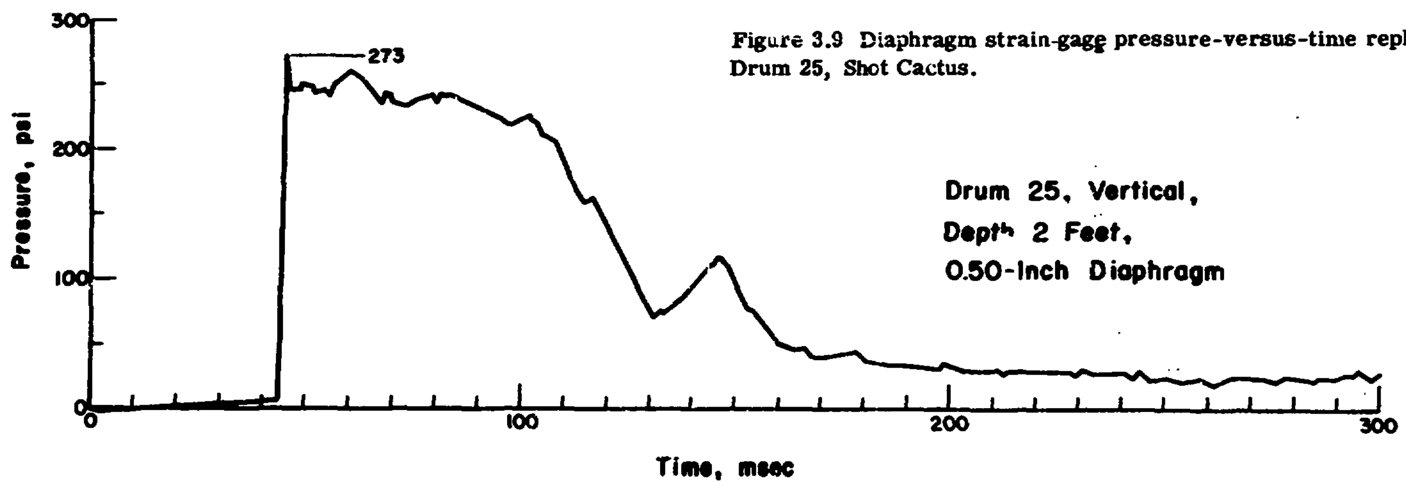

Figure 3.9 Diaphragm strain-gage pressure-versus-time replot, Drum 25, Shot Cactus.

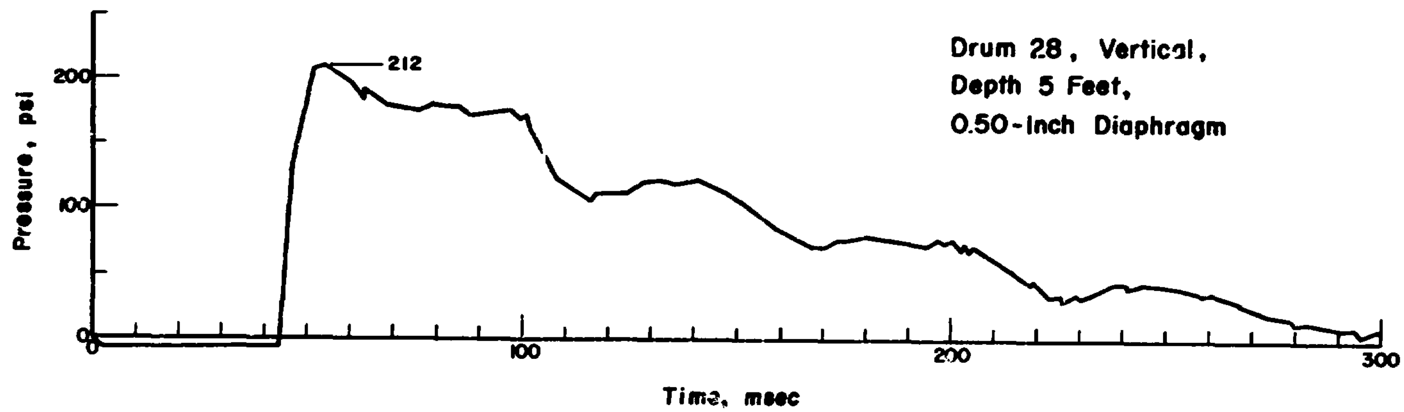

Figure 3.10 Diaphragm strain-gage pressure-versus-time replot, Drum 28, vertical, Shot Cactus.

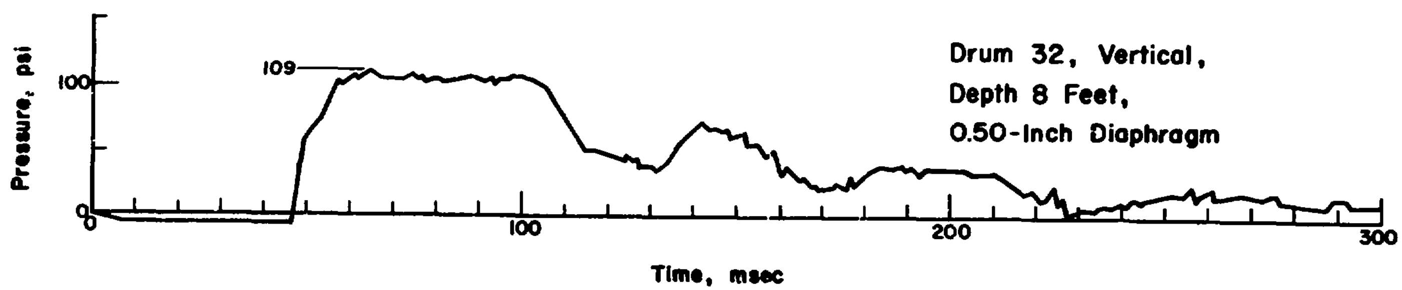

Figure 3.11 Diaphragm strain-gage pressure-versus-time replot, Drum 32, vertical, Shot Cactus.

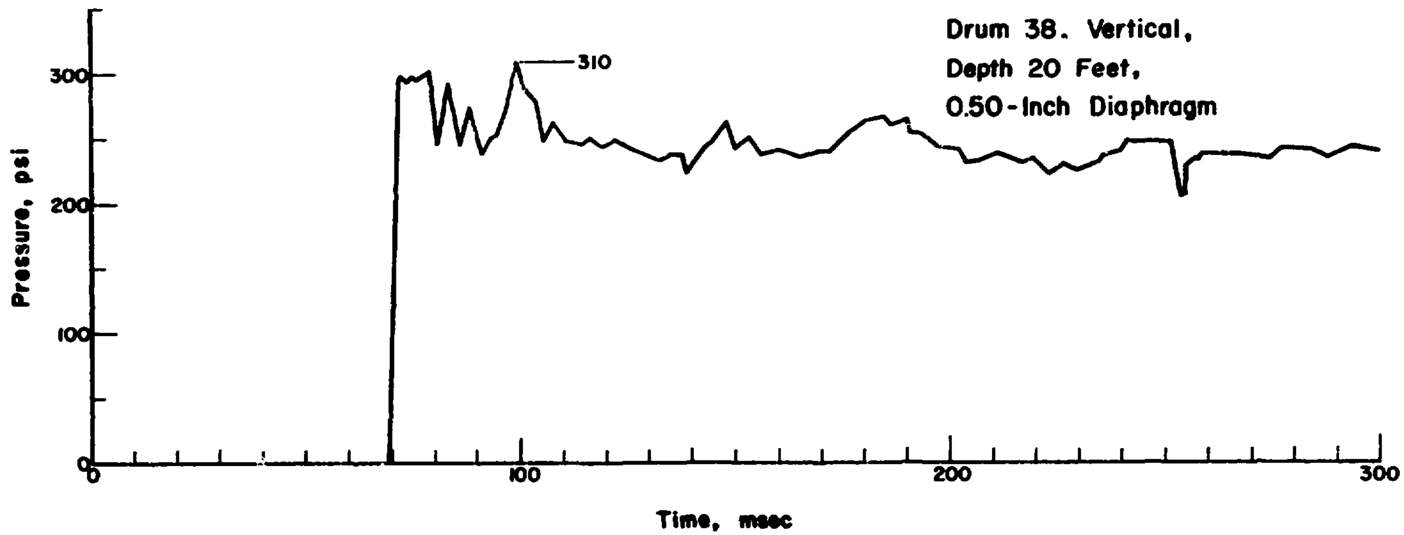

Figure 3.12 Diaphragm strain-gage pressure-versus-time replot, Drum 38, vertical, Shot Cactus.

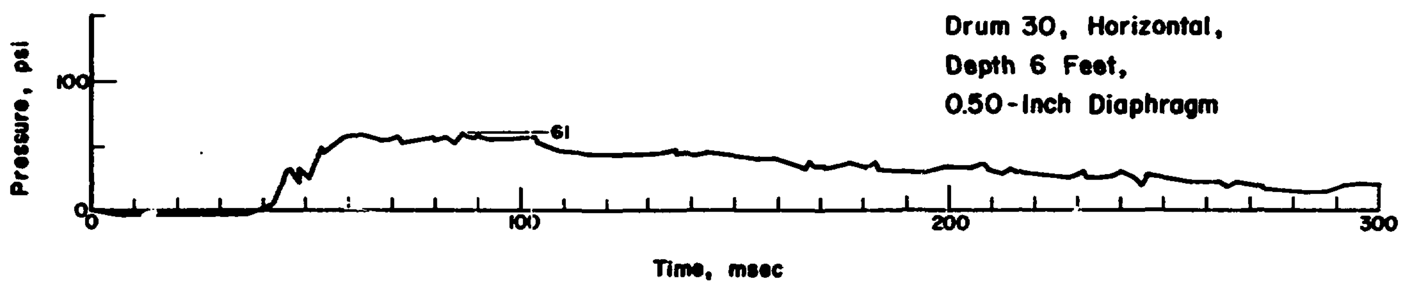

Figure 3.13 Diaphragm strain-gage pressure-versus-time replot, Drum 30, horizontal, Shot Cactus.

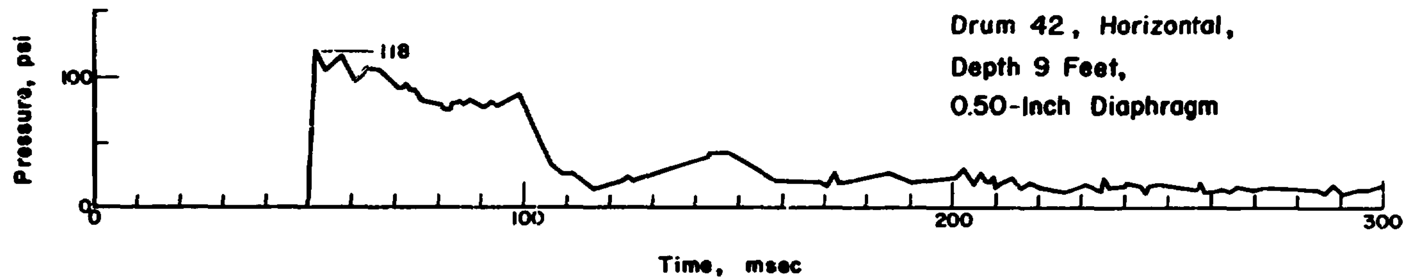

Figure 3.14 Diaphragm strain-gage pressure-versus-time replot, Drum 42, horizontal, Shot Cactus.

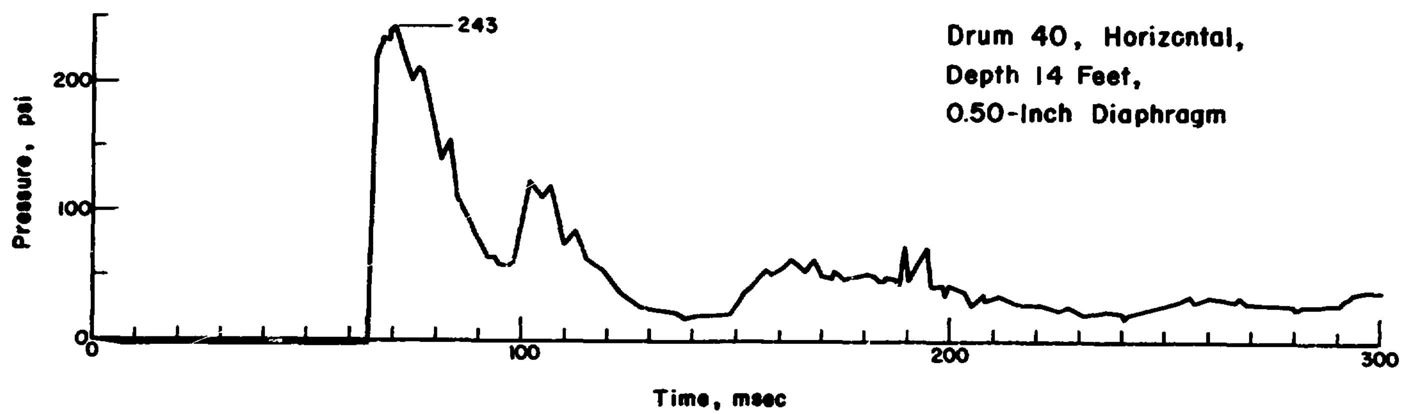

Figure 3.15 Diaphragm strain-gage pressure-versus-time replot, Drum 40, horizontal, Shot Cactus.

Chapter 4

DISCUSSION

4.1 SURFACE PRESSURES

The locations of the drums for the two shots were chosen so that the surface peak overpressure would be the same at both locations but, because of the large difference in yield, there would be an appreciable difference in the positive-phase durations. Although the measured surface peak overpressure at the location of the drums for Shot Cactus was about 20 percent higher than that at the location for Shot Koa, this difference in peak surface overpressure is not large enough to prevent determining the effects of the difference in positive-phase duration.

The pressure pulse from Shot Koa, as indicated by the BRL gages and the strain record from the surface 0.50-inch diaphragm, had a rise time of the order of 2 or 3 msec. After the first peak, there followed a period of from 30 to 40 msec during which the pressure varied widely and somewhat erratically. This was followed by a period of gradually decreasing pressure, with approximately the usual logarithmic decay. At a time greater than 200 msec after the arrival of the pulse, the pressure shown by the strain-gage record and the records from BRL Gages B and C was still greater than twice the ambient pressure. The record from Gage D, which indicates a crossover time of the order of 180 msec, had a baseline shift and cannot be regarded as indicating the true decay of the pulse.

The BRL gage records indicate that the pressure pulse from Shot Cactus had the same general shape as did that from Shot Koa. However, the rise portion of the pulse from Shot Cactus was more gradual and the decay portion steeper than the corresponding portions of the pulse from Shot Koa. Following the first peak the same period of fluctuating pressure appeared in the records from the BRL gages for Shot Cactus as from those for Shot Koa. The records from the strain-gage circuit of the surface 0.50-inch diaphragms are very similar in shape with the exception that the maximum pressure shown by the record from the surface drum for Shot Cactus is not the first peak. Instead, the second peak, which occurs about 3 msec later, is the maximum.

There is one point of disagreement between the record from the surface 0.50-inch diaphragm for Shot Cactus and the records from the BRL gages for the same shot. The pressure indicated by the diaphragm strain-gage record apparently approaches a minimum value of about 75 psi rather than 0 psi. A possible cause of this is the fact that the pressure on this diaphragm was unexpectedly high and was, in fact, beyond the calibration range of the electronic instrumentation. Although any resulting error in the computed maximum pressure would be small, there is a possibility that there would be discrepancies in the pressures shown by the pressure-versus-time replot because of unaccounted-for residual strains.

Because the two pressure pulses had similar shapes—and because the peak pressures were of about equal magnitude—the surface-pressure pulses from these two shots were suitable for determining the effect of positive-phase duration on the attenuation with depth of an air-induced soil pressure.

4.2 ATTENUATION WITH DEPTH OF AIR-INDUCED GROUND-TRANSMITTED PRESSURE

No pressure cells were used by this project; therefore, all the information regarding attenuation must come from measurements made on diaphragms. The pressures determined from measurements on these diaphragms are equivalent uniform pressures, because they were de-

termined from measured deflections and strains and the pressure-versus-deflection and pressure-versus-strain curves of Figures 2.6, 2.7, and 2.8. The pressure exerted by the soil on any diaphragm was probably not uniform over the surface of the diaphragm; thus, this equivalent uniform pressure is only an approximation of the soil pressure exerted against the diaphragm. Furthermore, because the flexibility of a diaphragm affects the pressure on the diaphragm, the pressure determined from the deformation of a diaphragm of a drum would not be equal to the pressure at the same depth in the soil deposit if no drum were present.

Despite the difference between the pressure on a diaphragm and that which would exist in the soil at the same depth if the drum were not present, diaphragm pressures can be used as a measure of the attenuation with depth of the air-induced soil pressure. This is the case because the ratio of diaphragm pressure to soil pressure in a uniform soil deposit should be essentially constant for the depths at which drums were buried for this test. It is unlikely that this ratio is constant at all depths for a soil deposit partly above and partly below the water table, because the properties of a soil change when it goes from an unsaturated to a saturated state. The question of how much change would occur in the ratio is unimportant because of the presence of the large water-transmitted pressure pulse (discussed below in relation to the effect of the water table on air-induced pressure transmission). The nonuniform pressure distribution should be about the same for all diaphragms of the same thickness. Furthermore, as described in Reference 1, the effect of diaphragm flexibility on the ratio of diaphragm pressure to soil pressure was the same for all depths of burial greater than the span. Therefore, even though the pressures determined from diaphragms of a given thickness are not the same as the soil pressures at the same depth, the ratio of a diaphragm pressure at one depth to that at another depth is the same as the ratio of the soil pressures at these depths.

This statement is true only if the effect of the ratio of the depth of burial to the span of the diaphragm can be neglected. In Reference 1 it was determined theoretically and demonstrated experimentally that small changes in depth had a large effect on the ratio of diaphragm pressure to soil pressure for depths less than half the span, and that this effect diminished as the depth of burial approached a value equal to the span. For depths greater than the span, there was negligible change in the ratio of the pressures with increase in depth. In this project, all diaphragms other than those at the surface were at depths greater than their span. For this reason, the effect of depth of burial on the ratio of diaphragm pressure to soil pressure is negligible, and diaphragm pressure variation with depth can be used as a measure of soil pressure variation with depth.

In the soil deposit studied, there is a discontinuity, namely the water table, which occurs within the region of interest. Part of the purpose of this project was to determine the effect of this discontinuity on the air-induced pressures in the soil below the water table and also the effect on the pressures exerted on structures below the water table. Unfortunately for this purpose, large-magnitude pressure pulses apparently were induced in the water beneath both detonations, and these pulses were transmitted horizontally to the locations of the drums. The apparent magnitude of the horizontally transmitted pressure was two to three times that of the surface peak overpressure at the range of the drums for Shot Koa. For Shot Cactus the apparent peak horizontal water-transmitted pressure was slightly less than the peak surface overpressure.

Because of the distance of the drums from Shot Koa, the water-transmitted pressure and the air-blast pressure should have arrived at different times. The existence of the water shock could have been substantiated by the transient-strain records from the drums below the water table; however, no transient-strain records were obtained from these drums because of damage to the instrument shelter from the blast and later damage to the records in attempting to remove them from the damaged shelter. Permanent-strain and permanent-deflection measurements were made on the diaphragms that were below the water table for Shot Koa and the evidence from these measurements supports the conclusion that the highest pressures on the diaphragms below the water table were produced by something other than the air-induced pressure.

Figure 4.1 shows the variation with depth of the equivalent uniform pressure on vertical-drum diaphragms of all three thicknesses for both Shots Cactus and Koa. All pressures shown in this figure were determined from deflection measurements and the pressure-versus-deflection curves of Figures 2.6 and 2.7.

Figure 4.2 is a normalized plot of the data shown in Figure 4.1. This presentation has the advantage of allowing comparison of the various pressure-versus-depth curves on the basis of the same surface pressure. Normalizing had the additional advantage of allowing the use of a linear scale for both axes in place of the semilogarithmic plot of Figure 4.1, while retaining a reasonable vertical scale. The linear vertical scale eliminates the inherent distortion of the logarithmic scale. In the normalization of the data shown in Figures 4.1 and 4.2, the surface pressure was taken to be that determined from deflection measurements on the diaphragm of the surface drum. Because of the failure of the 0.063-inch surface-drum diaphragm for both shots, the pressures on the 0.125-inch surface-drum diaphragms were assumed to represent the pressures on the 0.063-inch surface diaphragms as well. This should not introduce a serious approximation, because for Shot Koa there was only an 8-percent difference between the pressures on the surface 0.125- and 0.50-inch diaphragms; for Shot Cactus the difference was only 12 percent.

Figures 4.1 and 4.2 show that for Shot Koa the pressures on 0.063- and 0.125-inch diaphragms decreased a large amount between the surface and a depth of 5 feet (the water table was at a depth of 4.5 feet for Shot Koa) and that the pressures on the 0.50-inch diaphragms decreased a lesser amount. Diaphragm pressures at a depth of 8 feet showed an increase over pressures at 5 feet. For the 0.50-inch diaphragms the pressure increased from 251 psi to 672 psi whereas, for the 0.125-inch diaphragms, the increase was from 72 psi to 266 psi. The 0.063-inch diaphragm had failed at a depth of 8 feet; therefore, the pressure on this diaphragm must have been in excess of 200 psi, which was the lowest pressure at which a diaphragm of this thickness failed in the laboratory calibration tests. The pressure on the 5-foot-deep 0.063-inch diaphragm was 64 psi. Increases this large cannot be attributed to the air-induced pressure.

If the peak surface overpressure had been applied directly to the water surface and this pressure had then been transmitted directly to the diaphragms below the water surface, the maximum pressure that could have acted on the diaphragms would have been twice the air-induced pressure for a perfect reflection. Furthermore, this could only occur if the diaphragms were rigid, because any yielding of the diaphragm reduces the force exerted against it by the water. Neither can the increase in pressure be explained on the basis of a stress wave passing from a material with a lower seismic velocity to one with a higher velocity. It is difficult to conceive of a pressure greater than twice the surface peak overpressure being caused by an air-induced stress wave in a soil. Because the thinner diaphragms, at least, should have experienced pressures less than those in the surrounding soil, the measured diaphragm pressures cannot be explained on the basis of an air-induced soil pressure.

For Shot Koa, Figures 4.1 and 4.2 also show a further increase in diaphragm pressure between the depths of 8 feet and 13 feet and then a considerable decrease between 13 feet and 20 feet. It is interesting to note that the pressures on the 20-foot-deep diaphragms were almost exactly the same as the pressures on diaphragms of like thickness located at the surface. There is a possibility that the pressure at a depth of 13 feet was greatest because the permeability of the natural soil deposit was greatest at that depth. The deposit consists of alternating layers of loose sand and cemented material and there is, undoubtedly, a large difference in the permeability of the various layers. This must remain conjecture, because proof would require a far more extensive series of measurements than was made. It may or may not be true that the pressure everywhere in the trench was greatest at a depth of 13 feet. All the measurements at this depth were made within a few feet of each other; therefore, such a conclusion cannot be proved. Furthermore, the soil for several feet around the drums was excavated and replaced with beach sand. This should have reduced any effect of varying permeability in the surrounding natural deposit.

The situation for Shot Cactus is not as clear as that for Shot Koa, although it appears likely that a similar water-transmitted pressure pulse reached the drums. In this case, the distance from the detonation to the drums was such that the air-induced pressure should have reached the drums simultaneously, or very nearly so, with the water-transmitted pressure. The maximum pressure on any diaphragm below the water table for Shot Cactus was less than the peak surface overpressure at the location of the drums. Therefore, the pressures on drums below the water table could have been produced by a strictly air-induced loading. However, the pressure on the 20-foot-deep 0.125-inch diaphragm was nearly six times as great as that on a diaphragm of the same thickness at a depth of 8 feet. This is not consistent with a strictly air-induced soil pressure. Further evidence that a water-transmitted horizontal pulse existed is shown by the dynamic record from the 20-foot-deep drum. This record indicates an almost instantaneous pressure rise as opposed to the records from the other vertical drums which show an increasingly less-steep initial pressure rise with increasing depth. This abrupt change in shape is incompatible with the concept of a purely air-induced ground-transmitted pressure.

By itself, the record from this 20-foot-deep drum provides a somewhat weak basis for a conclusion that there existed a direct water-shock pressure. This record exhibits peculiarities other than that of a higher peak and sharper rise portion. The most obvious peculiarity is the fact that the record indicates essentially no decay of the pressure in 250 msec after the arrival of the pressure pulse. This is a highly unlikely occurrence, in view of the other pressure-versus-time records from diaphragms both above and below the water table. It strongly suggests a malfunction of the strain-gage circuit, although there is nothing to indicate whether this might have happened before or after the first peak. The 14-foot-deep horizontal drum, however, corroborates the sharp rise of pressure shown by the 20-foot vertical drum so this part of the record appears likely to be correct. There is further evidence that the pecularities of the record from this 20-foot-deep drum might have been caused by something other than the strain-gage circuit. The scratch gage record from this drum shows almost exactly the same behavior as does the strain-gage record. The peak pressure determined from transient deflection was 292 psi, but the permanent deflection was nearly as great as the transient deflection and corresponds to a peak pressure of 515 psi. The rod portion of this scratch gage was bent and consequently the peak pressure determined from the transient deflection might be in error. A correction was made for the bending, however, so the pressure should not be greatly in error.

Contrary to the situation shown by the drums for Shot Koa, there was no decrease in pressure below 13 feet shown by the drums for Shot Cactus. There was, however, a decrease in the pressure at a depth of 8 feet from that at 5 feet. Also, the pressure at 13 feet was greater than that at a depth of 8 feet.

Very little can be deduced regarding attenuation of the air-induced soil pressure below the water table because of the water-transmitted horizontal pressure. It is impossible to state with certainty whether the air-induced pressure predominated even near the water table. It would be reasonable to assume that the air-induced pressure was predominant at least to a depth of 5 feet for Shot Koa, because this is only 0.5 feet below the water surface. Figures 4.1 and 4.2 support this assumption in that they show that the pressure attenuated until the 5-foot depth was reached and then increased abruptly because of the horizontal water-transmitted pressure. From these figures it appears that for Shot Cactus the air-induced pressure was predominant to a depth of 8 feet, even though the water table was only 3.6 feet below the surface for this shot.

Comparison of the pressure-versus-depth curves of Figures 4.1 and 4.2 shows that at depths of 5 feet or less the pressures on any given thickness of diaphragm at any given depth were about the same for both shots. Because only one measurement was made at each depth for each shot, and because pressure measurements in soil tend to exhibit a great deal of scatter, these results can only be taken as an indication of the variation of diaphragm pressure with depth. The pressure-versus-depth curves show that the decrease in diaphragm pressure in the first 2 feet of depth was greater for Shot Cactus than it was for Shot Koa. The pressures on the 0.50-inch diaphragms for the two shots were almost exactly equal at depths of 2 and 5 feet,

whereas the surface pressure from Shot Cactus was more than 50 psi greater than that from Shot Koa. The situation is not so clear for the 0.125- and 0.063-inch diaphragms because of the apparent scatter of the data; however, the pressures on the diaphragms of corresponding thickness for the two shots are within about 15 psi of each other at depths of 2 and 5 feet, whereas the surface pressures differ by at least 50 psi.

Operation Plumbbob Project 1.7 concluded that the decrease in diaphragm pressure in the first 2 feet of depth is primarily a function of the relative compressibility of soil and drum, and that the best measure of the amount of attenuation is the further decrease of diaphragm pressure beyond a depth of 2 feet. The theory on which this conclusion was based is developed in Reference 1. A brief summary of the theory is presented later in this chapter under Section 4.4.

Because the decrease in diaphragm pressure beyond a depth of 2 feet was approximately the same for both Cactus and Koa (at least to the depth at which the horizontal water-transmitted pressure exceeded the air-induced pressure) it follows that the difference in the positive-phase durations of the two shots had no effect, apparently, on the attenuation of air-induced pressure in this soil.

Figure 4.3 shows a comparison of the variation of pressure with depth indicated by the 0.125-inch diaphragms for Shots Cactus and Koa of Operation Hardtack and by the near-location drums for Shot Priscilla of Operation Plumbbob. Figure 4.4 is a normalized plot of the same data. The drums for Shot Priscilla were buried in an unsaturated soil deposit consisting of a tan silt with a trace of clay. The surface peak overpressure at the near location for Shot Priscilla was about 225 psi, considerably lower than that for either Cactus or Koa. After the first 2 feet, in which the decrease in diaphragm pressure is mainly attributable to the effect of relative flexibility of the diaphragms and the soil, the decrease in diaphragm pressure was comparable for all three shots.

It was reasonably well established by Project 1.7, Operation Plumbbob, as well as by other projects previous to it, that attenuation with depth of an air-induced, ground-transmitted pressure is not greatly affected by the magnitude of the surface peak overpressure in the range of from 50 to 250 psi. The results obtained by the present project show that the difference between the positive-phase duration of a kiloton detonation and that of a megaton detonation also causes little or no change in the amount of attenuation. Figures 4.3 and 4.4 imply that soil type has little effect on attenuation. This implication is very likely to be merely fortuitous, because attenuation is undoubtedly affected by several soil properties and two soils seemingly very different could possess properties which, although individually different, might produce the same overall effect. Considerably more study of the problem of attenuation with depth of surface-applied soil pressures is needed before the soil properties that affect attenuation can be identified. In particular, there is need for laboratory studies under carefully controlled conditions.

4.3 COMPARISON OF HORIZONTAL AND VERTICAL DIAPHRAGM PRESSURES

Tables 3.3 and 3.6 summarize both the horizontal and vertical diaphragm pressures for Shots Koa and Cactus, respectively. For Shot Koa, there were only two horizontal drums, both of which had 0.50-inch diaphragms and were located below the water table. The 6-foot-deep diaphragm (for horizontal drums the effective depth is measured to the center of the diaphragm) lay in a region in which pressure was rapidly changing with depth. At a depth of 5 feet, near the top of the 6-foot-deep horizontal-drum diaphragm, the pressure on the 0.50-inch vertical-drum diaphragm was 251 psi, whereas that on the 8-foot-deep 0.50-inch diaphragm, a foot below the bottom of the 6-foot-deep horizontal-drum diaphragm, was 672 psi. Interpolating linearly, the value of vertical pressure which a diaphragm at a depth of 6 feet would have experienced was 391 psi. The horizontal-drum diaphragm at this depth was subjected to 266 psi or about 68 percent of the vertical pressure. At a depth of 14 feet the horizontal pressure was 536 psi or approximately 81 percent of the interpolated vertical pressure.

Five horizontal drums were included for Shot Cactus, one each at depths of 1, 3, 6, 9, and 14 feet. The 1-foot-deep drum had a 0.125-inch diaphragm, the 3-foot-deep drum a 0.063-inch

diaphragm, and the remaining three had 0.50-inch diaphragms. Interpolating again between the vertical drum measurements, in order to make direct comparisons, the following ratios of horizontal to vertical pressure were found: at 1 foot the horizontal pressure was 29 percent of the vertical; at 3 feet, 54 percent; at 6 feet, 39 percent; at 9 feet, 86 percent; and at 14 feet, 113 percent.

Only two horizontal drums were above the water table; these were the 1-foot- and 3-foot-deep drums on Shot Cactus. The 3-foot-deep diaphragm actually extended about 2 inches below the water table but the area of the diaphragm under water was negligible and the diaphragm can be considered as being completely above the water table for the purposes of this discussion. The ratios of horizontal-to-vertical pressure indicated by the horizontal drums at depths of 1 and 3 feet are within the range of values of this ratio obtained in Operation Plumbbob Project 1.7. The range of values from the earlier test was from 0.25 to 0.53. The ratios were determined for depths of 1, 4, and 9 feet to the center of the diaphragm. Of seven such ratios determined by Project 1.7, five were in the range of 0.43 to 0.47 and three were 0.45. If the one low value of 0.25 is disregarded, the results of Project 1.7 indicate an approximately constant ratio of horizontal-to-vertical pressure in an unsaturated soil.

As has been previously stated, the rapid decrease in diaphragm pressure in the first 2 feet of depth can be mostly attributed to the effect of depth-to-span ratio, i.e., depth of burial divided by the span of the structure, rather than to pressure attenuation with depth. The theoretical expression governing the decrease in diaphragm pressure in the first 2 feet of depth indicates that the pressure on a 0.125-inch diaphragm at a depth of 1 foot would be considerably less than the average of the surface pressure and the pressure at a depth of 2 feet. For this reason the ratio of horizontal-to-vertical pressure determined from the 1-foot-deep horizontal drum is likely to be too low. The ratio determined from the 3-foot-deep horizontal drum is much more likely to be correct because, as can be seen from Figures 4.1 and 4.2 there was less change in vertical-drum diaphragm pressure between 2 and 5 feet.

It would be expected that a condition approaching a hydrostatic stress state would exist below the water table. For Shot Koa, a true hydrostatic stress state never was attained—the horizontal pressure never exceeded 81 percent of the vertical. This does not agree very well with the concept of a horizontal water-transmitted pressure; however, a 33-percent variation from the true value of either horizontal or vertical pressure, which is well within the limits of probable scatter of the data, would account for the discrepancy. For Shot Cactus, the stress state approached hydrostatic at the 9-foot depth where the ratio of horizontal pressure to vertical pressure was 0.86. The horizontal pressure was 13 percent greater than the vertical pressure at a depth of 14 feet.

It appears that, at depths greater than 5 feet below the water table, there existed a state of stress that was hydrostatic or very nearly so. At shallower depths, where the air-induced pressure predominated, the stress state was not hydrostatic, but the vertical stress was considerably higher than the horizontal. Where the pressure state was hydrostatic, there was apparently also a large water-transmitted horizontal pressure. For this reason it cannot be determined from the results of this project whether a hydrostatic state of stress would exist at some distance below the water table if the air-induced pressure alone were acting.

The results from Shot Cactus indicate that the vertical pressure predominated at depths as much as 3 or 4 feet below the water table. This indicates that most of the pressure was carried by the soil skeleton at these depths, because whatever part was carried by the pore water would have been hydrostatic. If most of the soil pressure was carried by the skeleton, it could be expected that diaphragm flexibility would continue to be an important determinant of diaphragm pressure for a distance of several feet below the water table.

4.4 EFFECT OF DIAPHRAGM FLEXIBILITY

The basic concept of the effect of flexibility is that the deflection of a structural element reduces the soil pressure exerted on that element. The mechanism by which this occurs has not

been defined, but undoubtedly it is connected with the shear forces set up in the soil mass as it attempts to deform with the structure. In this situation, the more flexible a structural element becomes the less pressure is exerted on it, at least as long as the shear stresses in the soil do not exceed the ability of the soil to withstand such stresses. Likewise, with an extremely stiff element, it is possible to produce static pressures in excess of the soil pressure that would exist if no structure were present.

A comparison of the pressures on the three different thicknesses of diaphragm at each depth for Shot Cactus indicates that diaphragm flexibility had a considerable effect on the pressure on the diaphragms, both above and below the water table. However, the pressures on the diaphragms at depths of 13 and 20 feet for Shot Cactus, as presented in Tables 3.5 and 3.6, do not seem consistent with the idea of the most flexible diaphragms experiencing the lowest pressures. The pressure on the 0.125-inch diaphragm at the 13-foot depth was less than that on the more flexible 0.063-inch diaphragm at this depth. Similarly, the pressure on the 0.50-inch diaphragm at the 20-foot depth was less than that on the 0.125-inch diaphragm at the same depth.

The difference between the pressure on the 0.063-inch diaphragm and that on the 0.125-inch diaphragm at a depth of 13 feet was quite small as were the differences in the pressures on these two thicknesses of diaphragm at other depths. In view of the possibilities of scatter in the data, this discrepancy cannot be considered to be particularly important.

The situation at a depth of 20 feet is more serious in that not only was the pressure on the 0.125-inch diaphragm greater than that on the 0.50-inch diaphragm but also the deflection of the 0.125-inch diaphragm was greater than that of the 0.063-inch diaphragm. However, there was some doubt about the peak pressures indicated by the strain-gage record and the scratch gage on the 0.50-inch diaphragm at this depth. Both the strain-gage record and the scratch gage indicated residual deformations, i.e., strains and deflections, which were nearly equal to the maximum deformations. This strongly suggests that the actual peak pressures were considerably higher than the indicated peak pressures, in which case the 0.50-inch diaphragm pressure would have been greater than the 0.125-inch diaphragm pressure.

There is no such convenient explanation of the fact that deflection of the 0.125-inch diaphragm exceeded that of the 0.063-inch diaphragm. The values of the peak pressures assigned to these diaphragms are not in doubt, because permanent-deflection measurements were used to determine these values. There is, however, a possibility that the final position of one or more of the drums at the 20-foot depth differed from that at the time the drums were placed. The difference might have been in location, in orientation, or both. The placing of the drums at this depth was extremely difficult, and it was not possible to check the final positions of these drums after backfilling. A change in the position of the 0.063-inch diaphragm is a possible explanation of the fact that the deflection of this diaphragm was less than that of the 0.125-inch diaphragm.

The results for Shot Koa, shown in Figure 4.1, indicate that in all cases the pressure on the 0.125-inch diaphragm at a given depth was greater than that on the 0.063-inch diaphragm and less than that on the 0.50-inch diaphragm. The deflection of each 0.125-inch diaphragm was less than that of the 0.063-inch diaphragm and greater than that of the 0.50-inch diaphragm at the same depth. These results show that diaphragm flexibility is an important factor in determining diaphragm pressure.

In Reference 1, a theoretical analysis was made of the effect of diaphragm flexibility on the pressure acting against the diaphragm. This analysis yielded results that were in fairly good agreement with the results of the field-test measurements. For this reason it was decided to attempt to apply the same analysis to diaphragms above or slightly below the water table in this project. The presence of the water table makes this difficult, because the analysis considers only the deformation characteristics of the soil and is not adaptable to the consideration of pore-water pressures.

Below the water table, the effect of diaphragm flexibility is two-fold. First, the deflection mobilizes shear forces in the soil that is trying to deform with the diaphragm. This, in turn, gives rise to a situation in which the water attempts to flow through the voids and retain contact with the diaphragm. The pressure on a diaphragm thus becomes not only a function of the extent

to which shear forces are mobilized in the soil but also a function of the permeability of the soil. The analysis is incapable of considering the effects of permeability; the permeability of the soil in question under dynamic loads is unknown. In addition, the presence of the large-magnitude, horizontal, water-transmitted pressure has hopelessly obscured these effects beyond a few feet below the water table. For these reasons, the theoretical discussion will be limited to diaphragms either above or slightly below the water table, that is, to a depth of 5 feet below the ground surface for both shots. At these depths the pressure is carried almost entirely by the soil skeleton and the theoretical analysis is directly applicable.

The complete development of the analysis is given in Reference 1; only a brief summary will be given here.

In the analysis, the drum was represented by a hollow sphere and the surrounding soil by a concentric hollow sphere surrounding the first sphere and having an inner radius equal to the outer radius of this inner sphere. A pressure, P_0, was applied to the outer surface of the outer sphere and the pressure on the surface of the inner sphere was determined from the equations of the theory of elasticity. The analysis involved the solution of the case of radially symmetrical stress distribution. The equations of stress for a hollow sphere were written directly from the equations of equilibrium in polar coordinates.

Considering the small element of Figure 4.5, the equation of equilibrium in the y direction was written:

$$\frac{d}{dr}(\sigma_r r^2)\, d\theta^2 dr - 2\sigma_t\, r\, d\theta^2\, dr = 0$$

$$\frac{d}{dr}(r^2 \sigma_r) - 2r\sigma_t = 0$$

Differentiating:

$$r^2 \frac{d\sigma_r}{dr} + 2r\sigma_r - 2r\sigma_t = 0$$

$$2(\sigma_r - \sigma_t) + r\frac{d\sigma_r}{dr} = 0 \qquad (4.1)$$

Where: σ_r and σ_t = the radial and tangential stresses, respectively.

Because radial symmetry exists, the expressions for radial and tangential strains are simply:

$$\epsilon_r = \frac{du}{dr}, \quad \epsilon_t = \frac{u}{r}$$

Where: u = the radial displacement.

Continuity of radial stress and displacement across the interface of the spheres was considered. An expression for radial displacement was determined and, from this, expressions for all the stresses and strains were found. The expression for radial displacement was found by considering Equation 4.1 and finding relationships between u and $(\sigma_r - \sigma_t)$ and between u and $d\sigma_r/dr$. This was done as follows:

$$e = \epsilon_r + 2\epsilon_t = \frac{du}{dr} + \frac{2u}{r}$$

$$\sigma_r = \lambda e + 2G\epsilon_r = \lambda\frac{du}{dr} + 2\lambda\frac{u}{r} + 2G\frac{du}{dr} = (\lambda + 2G)\frac{du}{dr} + 2\lambda\frac{u}{r}$$

$$\sigma_t = \lambda e + 2G\epsilon_t = \lambda\frac{du}{dr} + 2\lambda\frac{u}{r} + 2G\frac{u}{r} = \lambda\frac{du}{dr} + 2(\lambda + G)\frac{u}{r}$$

$$\sigma_r - \sigma_t = \lambda\frac{du}{dr} + 2\lambda\frac{u}{r} + 2G\frac{du}{dr} - \lambda\frac{du}{dr} - 2\lambda\frac{u}{r} - 2G\frac{u}{r}$$

$$\sigma_r - \sigma_t = 2G\left(\frac{du}{dr} - \frac{u}{r}\right)$$

$$d\sigma_r = (\lambda + 2G)\frac{d^2u}{dr^2} + \frac{2\lambda}{r}\frac{du}{dr} - 2\lambda\frac{u}{r^2}$$

Where: λ = Lame's constant = $\frac{\nu E}{(1+\nu)(1-2\nu)}$, psi

G = shear modulus of elasticity = $\frac{E}{2(1+\nu)}$, psi

ν = Poisson's ratio

E = Young's modulus of elasticity, psi

e = compressibility = the sum of the three principal strains

Equation 4.1 can then be written:

$$\frac{d^2u}{dr^2} + \frac{2}{r}\frac{du}{dr} - \frac{2u}{r^2} = 0$$

This is an ordinary second-degree differential equation, the solution of which is:

$$u = Ar + \frac{B}{r^2}$$

The constants A and B vary with the properties and conditions of loading of the sphere. An expression for σ_r was found by considering the previously determined expression:

$$\sigma_r = (\lambda + 2G)\frac{du}{dr} + 2\lambda\frac{u}{r}$$

Because:

$$u = Ar + \frac{B}{r^2}$$

$$\frac{du}{dr} = A - \frac{2B}{r^3}$$

And:

$$\sigma_r = (3\lambda + 2G)A - \frac{4GB}{r^3}$$

If the notation and boundary conditions shown in Figure 4.6 are considered, the following equations can be written:

$$u_1|_{r=b} = u_2|_{r=b}$$

Or:
$$A_1 b + \frac{B_1}{b^2} = A_2 b + \frac{B_2}{b^2} \qquad (4.2)$$

$$\sigma_{r_1}|_{r=b} = \sigma_{r_2}|_{r=b}$$

Or:
$$(3\lambda_1 + 2G_1)A_1 - \frac{4G_1B_1}{b^3} = (3\lambda_2 + 2G_2)B_2 - \frac{4G_2B_2}{b^3} \qquad (4.3)$$

$$\sigma_{r_1}\Big|_{r=a} = -P_1$$

Or:

$$(3\lambda_1 + 2G_1)\,A_1 - \frac{4G_1 B_1}{a^3} = -P_1 = 0 \qquad (4.4)$$

$$\sigma_{r_2}\Big|_{r=c} = -P_0$$

Or:

$$(3\lambda_2 + 2G_2)\,A_2 - \frac{4G_2 B_2}{c^3} = -P_0 \qquad (4.5)$$

Solving Equations 4.2, 4.3, 4.4, and 4.5 simultaneously then putting the resulting expressions for A_1, A_2, B_1, and B_2 in terms of E and ν rather than λ and G gave:

$$A_1 = \frac{Pb^3(1-2\nu_1)}{(b^3-a^3)E_1} \qquad B_1 = \frac{Pa^3b^3(1+\nu_1)}{2(b^3-a^3)E_1}$$

$$A_2 = \frac{(Pb^3 - P_0c^3)(1-2\nu_2)}{(c^3-b^3)E_2} \qquad B_2 = \frac{(P-P_0)b^3c^3}{2(c^3-b^3)E_2}$$

Substituting these expressions in Equation 4.2 and simplifying the resulting expression gave:

$$\frac{P_0}{P} = \frac{1}{3}\,\frac{1+\nu_2}{1-\nu_2} + \frac{2}{3}\left(\frac{b}{c}\right)^3 \frac{1-2\nu_2}{1-\nu_2} + \frac{E_2}{E_1}\,\frac{1-\left(\frac{b}{c}\right)^3}{1-\left(\frac{a}{b}\right)^3}\,\frac{1}{1-\nu_2}\left[2(1-2\nu_1) + (1+\nu_1)\left(\frac{a}{b}\right)^3\right] \qquad (4.6)$$

This expression was further simplified by considering the relative compressibility of the inner sphere and that of a solid sphere having the same outer radius but being made of the same material as the outer sphere. This is equivalent to comparing the compressibility of a buried structure with that of the soil it replaced.

The compressibility e of a body is the change in volume of the body divided by the original volume, or $\Delta V/V$. For a sphere of Radius b:

$$e = \frac{\Delta V}{V} = 3\frac{u}{r} = \frac{3u}{b}$$

Because $\sigma_r = \sigma_t$ and $\epsilon_r = \epsilon_t = \frac{u}{r}$, for a solid sphere having elastic constants E_2 and ν_2:

$$u_0 = \frac{b(1-2\nu_2)p}{E_2}$$

and for a hollow sphere of inner radius a and outer radius b having elastic constants E_1 and ν_1:

$$u = -\frac{1}{2}\,\frac{Pb}{E_1}\,\frac{1}{b^3-a^3}\left[2(1-2\nu_1)\,b^3 + (1+\nu_1)\,a^3\right]$$

The relative compressibility of the two spheres is then:

$$\frac{e}{e_0} = \frac{u}{u_0} = \frac{1}{2}\,\frac{E_2}{E_1}\,\frac{1}{b^3-a^3}\,\frac{1}{1-2\nu_2}\left[2(1-2\nu_1)\,b^3 + (1+\nu_1)\,a^3\right]$$

Or:

$$\frac{E_2}{E_1} = 2\frac{e}{e_0}\left[1-\left(\frac{a}{b}\right)^3\right](1-2\nu_2)\,\frac{1}{2(1-2\nu_1) + (1+\nu_1)\left(\frac{a}{b}\right)^3}$$

This expression for E_2/E_1 was then substituted in Equation 4.6, giving:

$$\frac{P_0}{P} = \frac{1}{3}\ \frac{1+\nu_2}{1-\nu_2} + \frac{2}{3}\left(\frac{b}{c}\right)^3 \frac{1-2\nu_2}{1-\nu_2} + \frac{2}{3}\ \frac{1-2\nu_2}{1-\nu_2}\left[1-\left(\frac{b}{c}\right)^3\right]\frac{e}{e_0} \tag{4.7}$$

If this expression is applied to the drum, the compressibility can be determined by considering only the deflection of the diaphragm, because the rest of the drum is rigid. If the deflected shape of the diaphragm is assumed to be a spherical cap, the volume change due to a deflection h would be:

$$\Delta V = \frac{\pi h}{24}\ (3a^2 + 4h^2)$$

Where: a = the diameter of the diaphragm, 18 inches in this case.

In Reference 1, the drums described had two diaphragms, one on each end, and the compressibility of the drums, which had somewhat different pressures acting on the two diaphragms was determined, in effect, by considering two half-drums each of which had a diaphragm at one end and a rigid plate at the other. These two half-drums were equivalent to the actual drum in compressibility characteristics. This approach eliminated the question of the effect of the deformation of one end diaphragm on the deformation of the diaphragm at the opposite end of the drum. The calculation of the compressibility in this manner introduced only a minor approximation in Reference 1; doing so in this project could introduce a more serious approximation because there was only one end diaphragm. The other end of the drum was a rigid plate. It seems more reasonable, however, to make such an approximation, because considering overall drum compressibility as the only determinant of diaphragm pressure at depths of 5 feet or less is more of an approximation than considering the drum as two half-drums. It must be remembered that the analysis is based on an oversimplified theory that can only be substantiated by further study and determination of factors such as dynamic soil properties and the effects of relative stiffness of the various parts of the drum. Until these factors become known, any agreement between diaphragm-pressure predictions and field-test results can be considered as only an indication of the validity of the assumptions made in the analysis.

If the assumption of two half-drums is made, the compressibility e is:

$$e = \frac{\Delta V}{V} = \frac{255h}{10{,}850} + \frac{1.05h^3}{10{,}850} \approx 0.0234\,h \tag{4.8}$$

The expression for the compressibility of the replaced soil mass under a hydrostatic pressure P_0 is:

$$e_0 = \frac{3(1-2\nu_2)\,P_0}{E_2} \tag{4.9}$$

Because the lateral pressure was much less than the vertical pressure, an adjusted value of P_0 was used in this expression. If it is assumed that there was no lateral strain in the soil because of the restraint offered by the surrounding soil, the ratio of horizontal-to-vertical pressures found in this project corresponds to a Poisson's ratio of 0.30. If the relative areas of the ends of the drum and the sidewalls are considered, the average pressure is found to be 0.62 times the vertical pressure.

Very little information is available concerning the deformation characteristics of the sand used as backfill in the present project. Some seismic velocity measurements on this soil deposit indicate that the modulus of deformation is about 11,000 psi in the dry state. This value can be considered as representative only of the initial tangent modulus of the soil because of the low stress levels involved in seismic velocity determinations. Then, the secant or effective modulus of deformation for such a sand should be approximately 9,000 psi (Reference 3). If this value is substituted in Equation 4.9, together with the average pressure of 0.62 P_0, the

resulting expression is:

$$e_0 = \frac{3(1-0.6)}{9{,}000} = (0.62\ P_0) = 0.0000826\ P_0 \tag{4.10}$$

Using Equations 4.8 and 4.10 gives:

$$\frac{e}{e_0} = \frac{0.0234}{0.0000826}\frac{h}{P_0} = 284\frac{h}{P_0}$$

The dimensions of h/P_0 are cubic inches per pound.

Substituting this expression for e/e_0 in Equation 4.7 together with $\nu_2 = 0.30$ gives:

$$\frac{P_0}{P} = 0.619 + 0.381\left(\frac{b}{c}\right)^3 + 108\left[1-\left(\frac{b}{c}\right)^3\right]\frac{h}{P_0} \tag{4.11}$$

A simple relationship between b/c and depth-to-span ratio for a drum can be determined by considering the depth of burial to correspond to c – b and the span to 2b. Then the depth-to-span ratio is simply c–b/2b. Because the span of the drum is 2 feet, the depth-to-span ratio becomes:

$$\frac{\text{depth}}{\text{span}} = \frac{d}{2} = \frac{c-b}{2b}$$

$$\frac{c}{b} = d+1$$

where b, c, and d are in feet.

Equation 4.11 can then be written:

$$\frac{P_0}{P} = 0.619 + 0.381\frac{1}{(d+1)^3} + 108\left[1-\frac{1}{(d+1)^3}\right]\frac{h}{P_0} \tag{4.12}$$

For an infinite depth of burial, this equation becomes:

$$\frac{P_0}{P} = 0.619 + 108\frac{h}{P_0} \tag{4.13}$$

For values of d greater than 1.5 feet, Equation 4.12 yields values of P_0/P very nearly the same as the values obtained from Equation 4.13; for d = 1 foot, the difference is not great, and for d = 2 feet the difference is negligible.

Table 4.1 shows a comparison of measured diaphragm pressures with pressures calculated using Equation 4.13. The values of soil pressure P_0 were estimated on the assumption that the soil pressure decreases at a constant rate with respect to depth and that this rate is the same as that at which diaphragm pressure decreases below a depth of 2 feet. The basis for this assumption has been previously discussed. The rate of diaphragm-pressure decrease was determined from the diaphragms at depths of 2 feet and 5 feet. The surface diaphragms were not considered because, as has been previously mentioned, the decrease in diaphragm pressure in the first 2 feet of depth is principally because of the effect of depth-to-span ratio rather than because of attenuation of the soil pressure. Results from drums below a depth of 5 feet were not used because of the predominance of the water-transmitted pressure below these depths. The soil pressures P_0 were determined, in effect, by determining an average slope of pressure decrease for all thicknesses of diaphragm from the pressures at depths of 2 and 5 feet in Figure 4.1, then drawing a line parallel to this and intersecting the pressure axis at the value corresponding to the surface pressure.

The measured and predicted pressures compare very well, considering the possible scatter of pressure measurements on objects buried in soil. This agreement should not be construed as complete justification for all the assumptions that have been made in the analysis, however,

but only as an indication that the analysis considers at least some of the most important variables.

TABLE 4.1 COMPARISON OF MEASURED AND PREDICTED DIAPHRAGM PRESSURES

Shot	Drum Depth	Diaphragm Thickness	Soil Pressure, P_0	Theoretical Predicted Pressure, P	Pressure Measured from Deflection, P_m	Difference, $P-P_m$
	ft	inch	psi	psi	psi	psi
Cactus	2	0.063	281	64	68	−4
		0.125		101	85	+16
		0.500		295	298	−3
	5	0.063	251	57	71	−14
		0.125		90	89	+1
		0.500		264	255	+9
Koa	2	0.063	301	68	76	−8
		0.125		108	100	+8
		0.500		316	301	+15
	5	0.063	269	58	64	−6
		0.125		97	72	+25
		0.500		282	251	+31

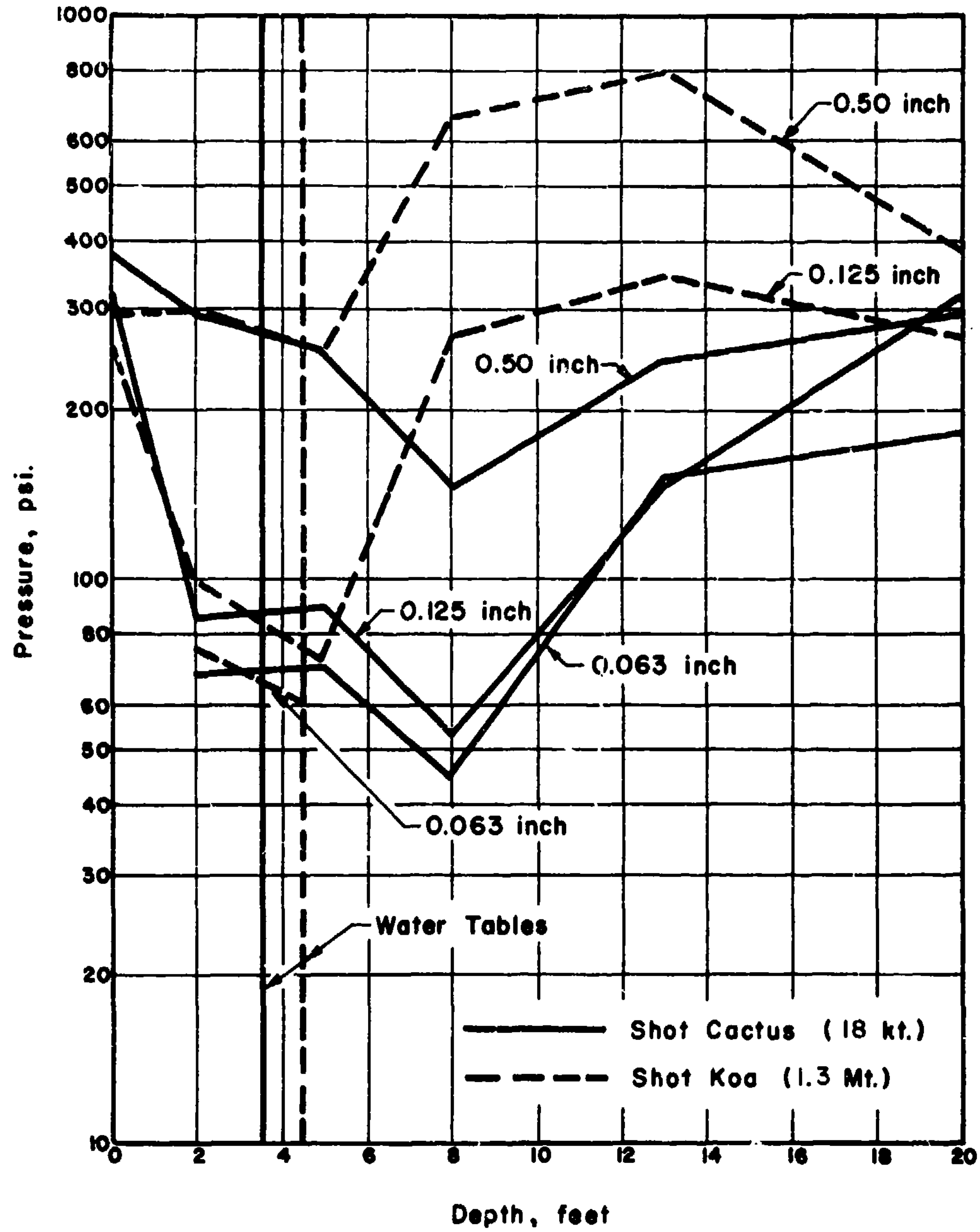

Figure 4.1 Variation of diaphragm pressure with depth, Shots Cactus and Koa, vertical drums.

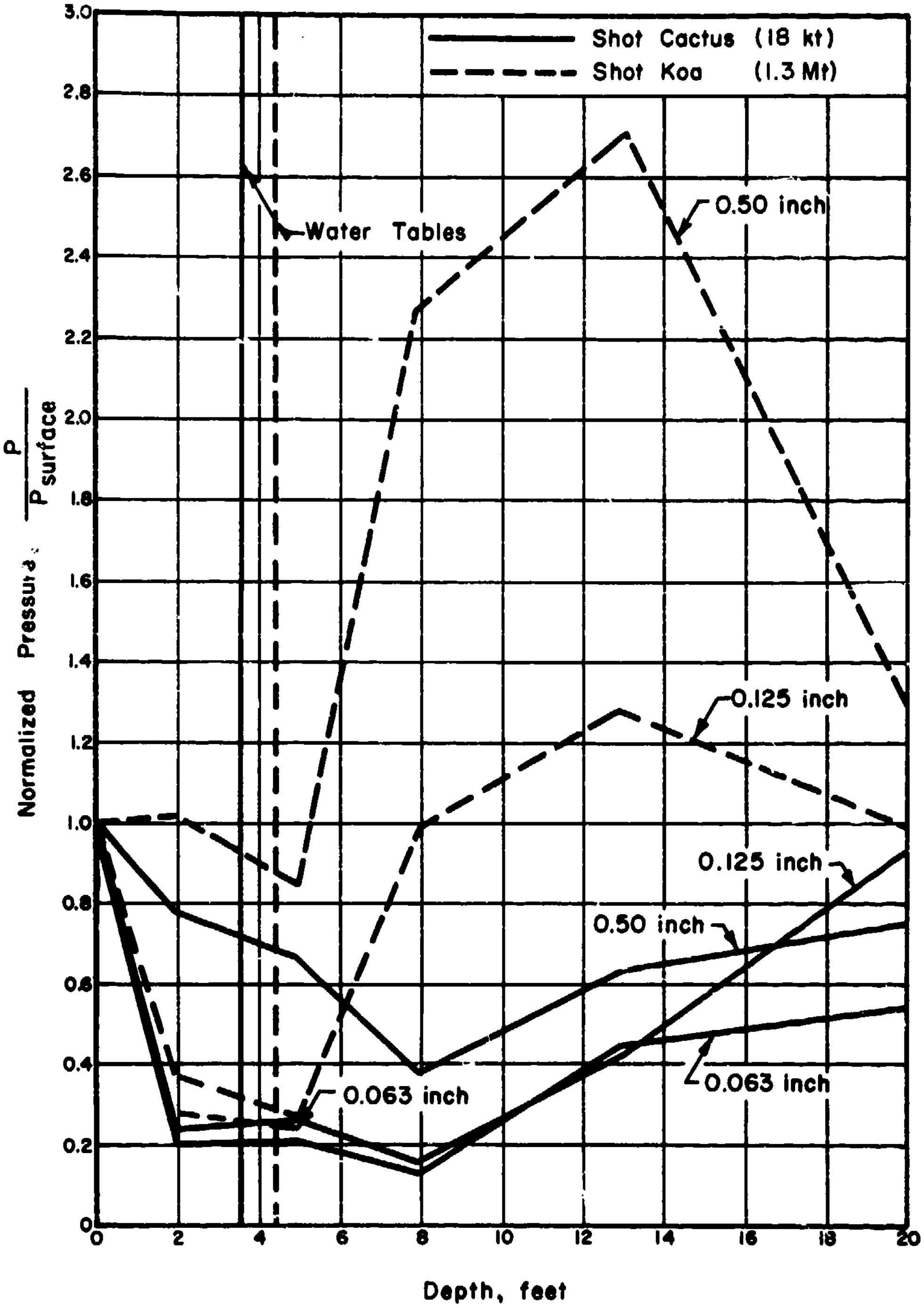

Figure 4.2 Normalized plot of variation of diaphragm pressure with depth, Shots Cactus and Koa, vertical drums.

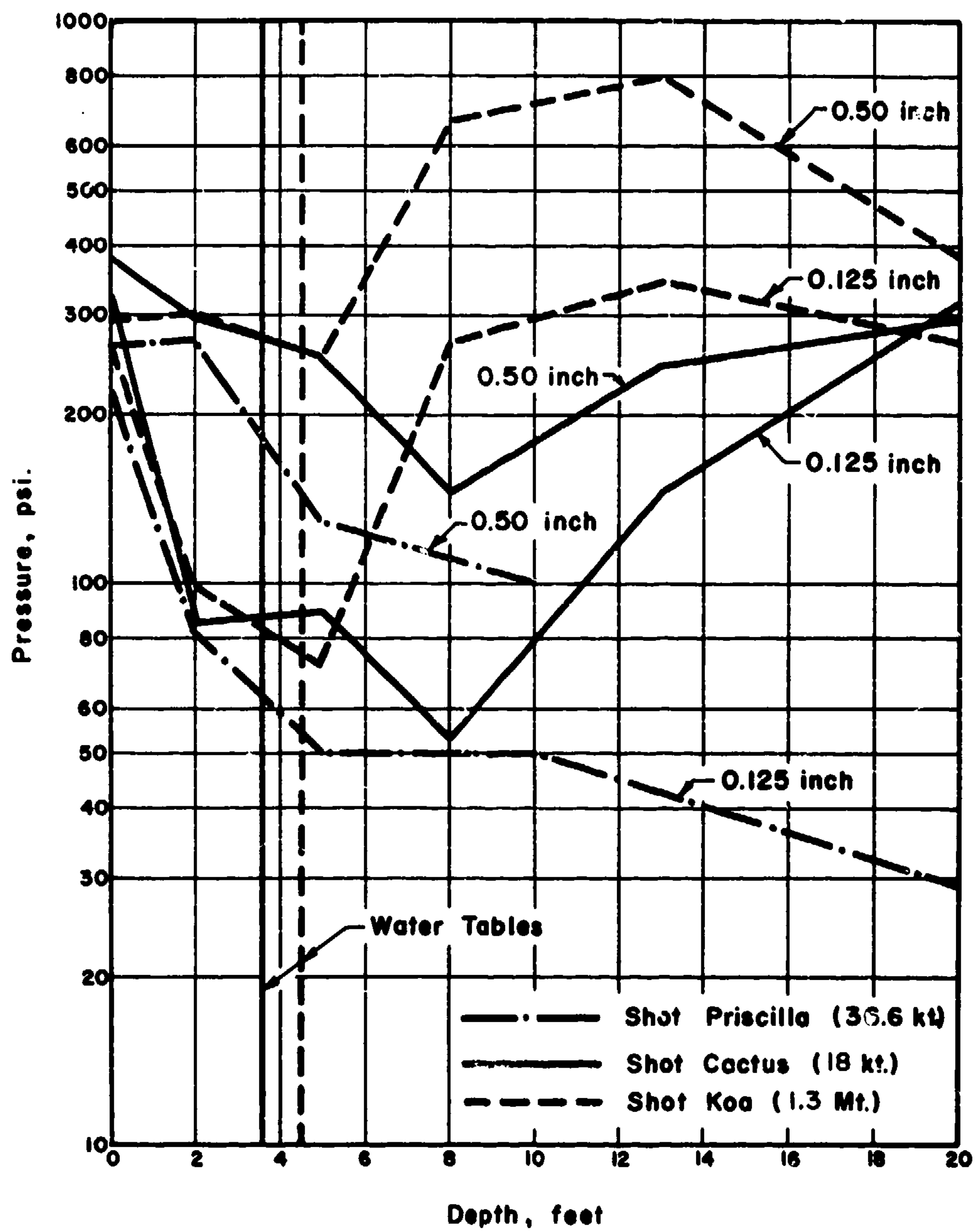

Figure 4.3 Variation of diaphragm pressure with depth, Shots Cactus, Koa, and Priscilla, 0.125- and 0.50-inch diaphragms, vertical drums.

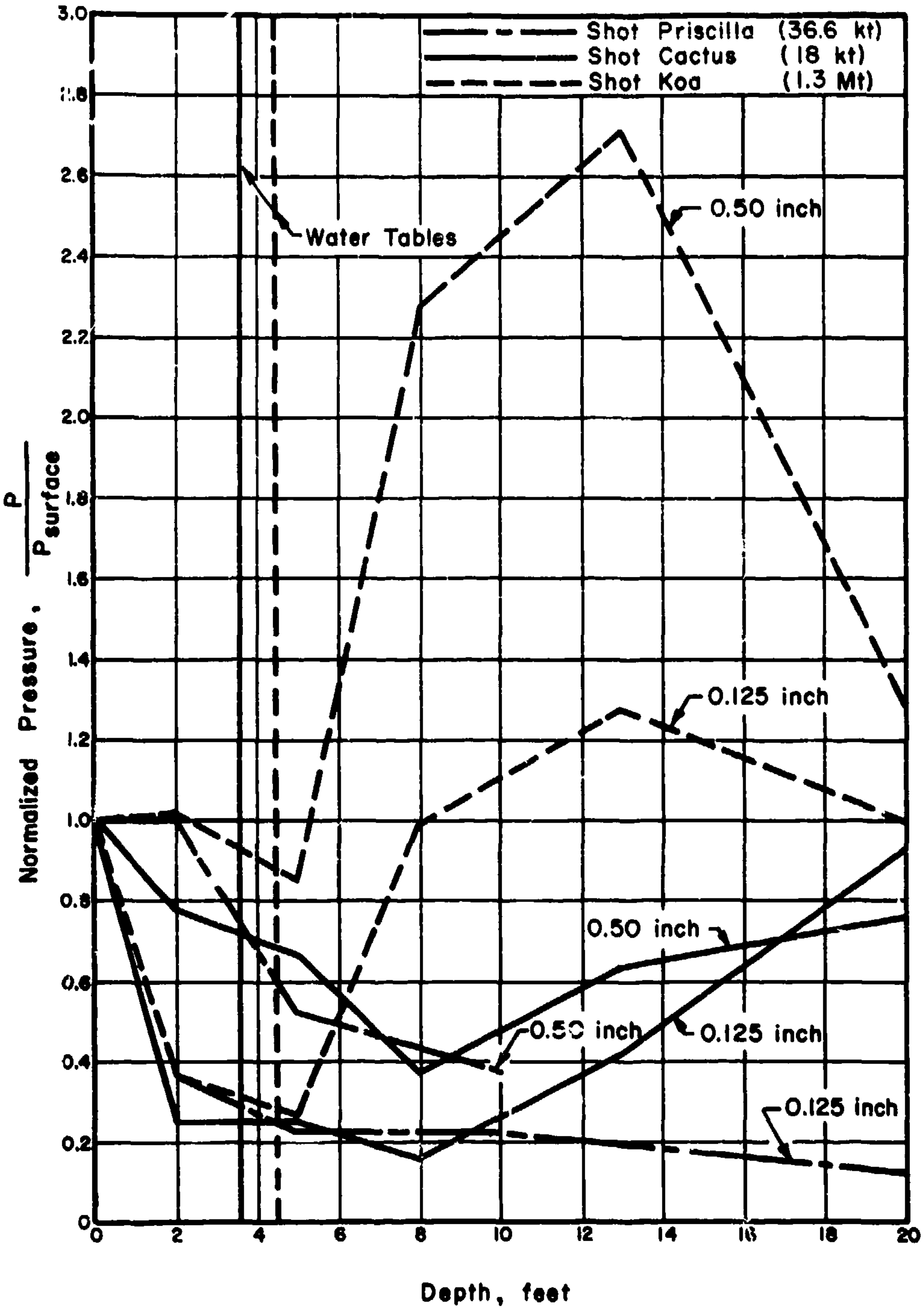

Figure 4.4 Normalized plot of variation of diaphragm pressure with depth, Shots Cactus, Koa, and Priscilla, 0.125- and 0.50-inch diaphragms, vertical drums.

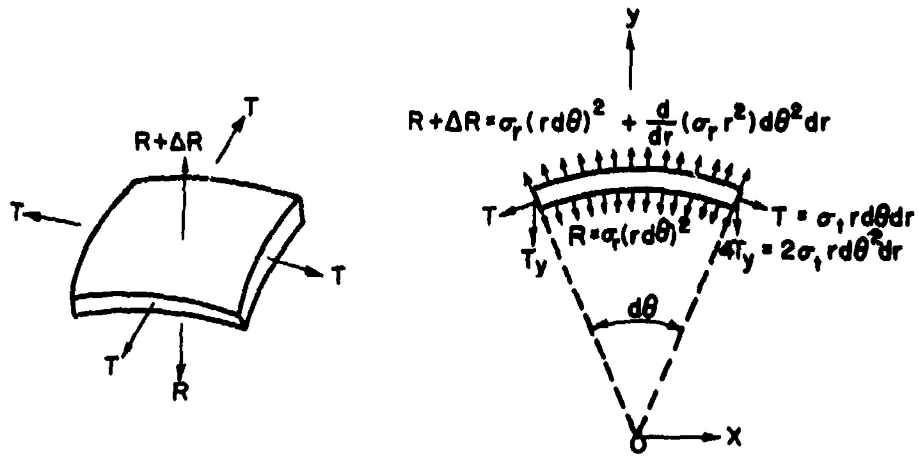

Figure 4.5 Loading on spherical model.

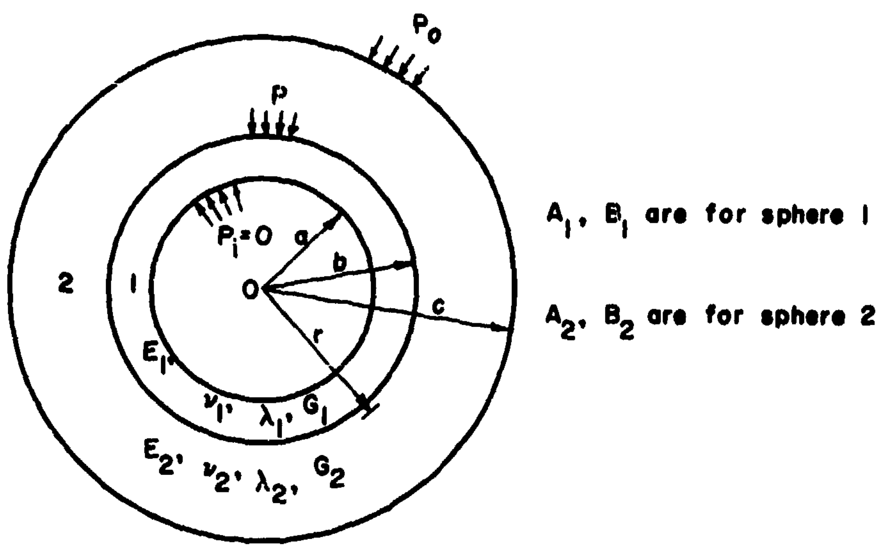

Figure 4.6 Nomenclature for spherical model.

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

On the basis of a very limited amount of data and in view of the apparent presence of a large water-transmitted pressure pulse, the following conclusions can be made:

1. For a soil deposit consisting of loose beach sand such as that found at EPG, there is considerable attenuation of an air-induced, ground-transmitted pressure. This is true not only above the water table but also for at least a few feet below it. The presence of the horizontal water-transmitted pressure obscured this effect at depths greater than this. The amount of this attenuation in the soil deposit is approximately the same as was found in the tan silt deposit at NTS, which was about 20 percent in the first 5 feet of depth.

2. The difference between the positive-phase duration of a kiloton detonation and that of a megaton detonation appears to have no appreciable effect on the attenuation with depth of an air-induced pressure in a loose beach sand deposit such as that found at EPG.

3. Where the air-induced pressure predominates, the horizontal pressure is much less than the vertical. At EPG, the ratio of these pressures was about 0.50 at all depths from the surface down to a few feet below the water table. Approximately the same value was found at NTS during Operation Plumbbob.

Where the horizontal water shock was predominant, the stress state in the soil was approximately hydrostatic which was to be expected because undrained saturated soil behaves much as a liquid. No conclusions can be drawn regarding the stress state in a saturated soil deposit subjected to strictly air-induced pressure, because the horizontal water-transmitted pressure exceeded the air-induced pressure at depths where a hydrostatic pressure would be expected to exist under air-induced pressure loading.

4. The flexibility of the diaphragms has a considerable effect on the pressures acting on them whether they are located above or below the water table. When the overall compressibility of the drum is much greater than that of the soil it replaces, the pressure on the diaphragm is materially less than that in the soil surrounding the drum. This difference can be more than 50 percent and is almost completely developed in a depth of burial equal to the span of the drum.

5. The results of the present test agree with the theory developed in Reference 1. However, this theory includes a number of simplifying assumptions and some fairly crude approximations. Further study is required to refine the analysis.

5.2 RECOMMENDATIONS

Carefully-controlled laboratory tests should be conducted to determine the dynamic behavior of soils. This remains the most important unknown factor in the problem of buried structures subjected to dynamic loads, with regard to both attenuation of the air-induced pressure with depth, and dynamic soil-structure interaction. A great deal is known about the behavior of structures subjected to dynamic loads. Knowledge of the behavior of soil under such loads must advance to a comparable level before the interaction problem can be solved. A good start has been made by some investigators (Reference 3), but much remains to be done to determine dynamic soil properties sufficiently well for the purposes of this analysis.

Desirable extensions of the sphere analysis include: (1) consideration of the dynamic case; (2) determination of the effects of the shape of the structure; and (3) determination of the effects

of the relative stiffness of various parts of the structure on the distribution of pressure over its surface.

The results show a necessity for further study of the coupling of surface detonations with the pore water in soil deposits having water tables near the surface. The results of this project indicate that the pressure thus induced in the pore water may be at least as important as the air-induced pressures in producing loads on buried structures.

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59 Director, U.S. Naval Research Laboratory, Washington 25, D.C. ATTN: Mrs. Katherine H. Cass
60- 61 Commander, U.S. Naval Ordnance Laboratory, White Oak, Silver Spring 19, Md.
62 Director, Material Lab. (Code 900), New York Naval Shipyard, Brooklyn 1, N.Y.
63 Commanding Officer and Director, Navy Electronics Laboratory, San Diego 52, Calif.
64 Commanding Officer, U.S. Naval Mine Defense Lab., Panama City, Fla.
65- 66 Commanding Officer, U.S. Naval Radiological Defense Laboratory, San Francisco, Calif. ATTN: Tech. Info. Div.
67- 68 Commanding Officer and Director, U.S. Naval Civil Engineering Laboratory, Port Hueneme, Calif. ATTN: Code L31
69 Commanding Officer, U.S. Naval Schools Command, U.S. Naval Station, Treasure Island, San Francisco, Calif.
70 Superintendent, U.S. Naval Postgraduate School, Monterey, Calif.
71 Officer-in-Charge, U.S. Naval School, CEC Officers, U.S. Naval Construction Bn. Center, Port Hueneme, Calif.
72 Commanding Officer, Nuclear Weapons Training Center, Atlantic, U.S. Naval Base, Norfolk 11, Va. ATTN: Nuclear Warfare Dept.
73 Commanding Officer, Nuclear Weapons Training Center, Pacific, Naval Station, San Diego, Calif.
74 Commanding Officer, U.S. Naval Damage Control Tng. Center, Naval Base, Philadelphia 12, Pa. ATTN: ABC Defense Course
75 Commanding Officer, Naval Air Material Center, Philadelphia 12, Pa. ATTN: Technical Data Br.
76 Commanding Officer U.S. Naval Air Development Center, Johnsville, Pa. ATTN: NAS, Librarian
77 Commanding Officer, U.S. Naval Medical Research Institute, National Naval Medical Center, Bethesda, Md.
78- 79 Commanding Officer and Director, David W. Taylor Model Basin, Washington 7, D.C. ATTN: Library

80 Commanding Officer and Director, U.S. Naval Engineering Experiment Station, Annapolis, Md.

81 Commander, Norfolk Naval Shipyard, Portsmouth, Va. ATTN: Underwater Explosions Research Division

82 Commandant, U.S. Marine Corps, Washington 25, D.C. ATTN: Code AO3H

83 Director, Marine Corps Landing Force, Development Center, MCS, Quantico, Va.

84 Commanding Officer, U.S. Naval CIC School, U.S. Naval Air Station, Glynco, Brunswick, Ga.

85- 87 Chief, Bureau of Naval Weapons, Navy Department, Washington 25, D.C. ATTN: RR12

AIR FORCE ACTIVITIES

88 Air Force Technical Application Center, HQ USAF, Washington 25, D. C.

89 Hq. USAF, ATTN: Operations Analysis Office, Office, Vice Chief of Staff, Washington 25, D. C.

90 Director of Civil Engineering, HQ. USAF, Washington 25, D.C. ATTN: AFOCE-ES

91-101 Hq. USAF, Washington 25, D.C. ATTN: AFCIN-3D1

102 Director of Research and Development, DCS/D, HQ. USAF, Washington 25, D.C. ATTN: Guidance and Weapons Div.

103 The Surgeon General, HQ. USAF, Washington 25, D.C. ATTN: Bio.-Def. Pre. Med. Division

104 Commander, Tactical Air Command, Langley AFB, Va ATTN: Doc. Security Branch

105 Commander, Air Defense Command, Ent AFB, Colorado. ATTN: Operations Analysis Section, ADOOA

106 Commander, Hq. Air Research and Development Command, Andrews AFB, Washington 25, D.C. ATTN: RDRWA

107 Commander, Air Force Ballistic Missile Div. HQ. ARDC, Air Force Unit Post Office, Los Angeles 45, Calif. ATTN: WDSOT

108 Commander, Second Air Force, Barksdale AFB, La. ATTN: Operations Analysis Office

109-110 Commander, AF Cambridge Research Center, L. G. Hanscom Field, Bedford, Mass. ATTN: CRQST-2

111-115 Commander, Air Force Special Weapons Center, Kirtland AFB, Albuquerque, N. Mex. ATTN: Tech. Info. & Intel. Div.

116-117 Director, Air University Library, Maxwell AFB, Ala.

118 Commander, Lowry Technical Training Center (TW), Lowry AFB, Denver, Colorado.

119 Commandant, School of Aviation Medicine, USAF Aerospace Medical Center (ATC), Brooks AFB, Tex. ATTN: Col. G. L. Hekhuis

120-122 Commander, Wright Air Development Center, Wright-Patterson AFB, Dayton, Ohio. ATTN: WCACT (For WCOSI)

123-124 Director, USAF Project RAND, VIA: USAF Liaison Office, The RAND Corp., 1700 Main St., Santa Monica, Calif.

125 Commander, Rome Air Development Center, ARDC, Griffiss AFB, N.Y. ATTN: Documents Library, RCSSLD

126 Commander, Air Technical Intelligence Center, USAF, Wright-Patterson AFB, Ohio. ATTN: AFCIN-4B1a, Library

127 Headquarters, 1st Missile Div., USAF, Vandenberg AFB, Calif. ATTN: Operations Analysis Office

128 Assistant Chief of Staff, Intelligence, Hq. USAFE, APO 633, New York, N.Y. ATTN: Directorate of Air Targets

129 Commander-in-Chief, Pacific Air Forces, APO 953, San Francisco, Calif. ATTN: PFCIE-MB, Base Recovery

OTHER DEPARTMENT OF DEFENSE ACTIVITIES

130 Director of Defense Research and Engineering, Washington 25, D.C. ATTN: Tech. Library

131 Chairman, Armed Services Explosives Safety Board, DOD, Building T-7, Gravelly Point, Washington 25, D.C.

132 Director, Weapons Systems Evaluation Group, Room 1E880, The Pentagon, Washington 25, D.C.

133-136 Chief, Defense Atomic Support Agency, Washington 25, D.C. ATTN: Document Library

137 Commander, Field Command, DASA, Sandia Base, Albuquerque, N. Mex.

138 Commander, Field Command, DASA, Sandia Base, Albuquerque, N. Mex. ATTN: FCTG

139-140 Commander, Field Command, DASA, Sandia Base, Albuquerque, N. Mex. ATTN: FCWT

141 Commander-in-Chief, Strategic Air Command, Offutt AFB, Neb. ATTN: OAWS

142 U.S. Documents Officer, Office of the United States National Military Representative - SHAPE, APO 55, New York, N.Y.

ATOMIC ENERGY COMMISSION ACTIVITIES

143-145 U.S. Atomic Energy Commission, Technical Library, Washington 25, D.C. ATTN: For DMA

146-147 Los Alamos Scientific Laboratory, Report Library, P.O. Box 1663, Los Alamos, N. Mex. ATTN: Helen Redman

148-152 Sandia Corporation, Classified Document Division, Sandia Base, Albuquerque, N. Mex. ATTN: H. J. Smyth, Jr.

153-164 University of California Lawrence Radiation Laboratory, P.O. Box 808, Livermore, Calif. ATTN: Clovis G. Craig

165 Office of Technical Information Extension, Oak Ridge, Tenn. (Master)

166-195 Office of Technical Information Extension, Oak Ridge, Tenn. (Surplus)

SSTS 26 June 1995

MEMORANDUM FOR DEFENSE TECHNICAL INFORMATION CENTER
ATTN: OCD/MR. BILL BUSH

SUBJECT: Declassification of Report

The following reports have been reviewed by the Defense Nuclear Agency Security Office (ISTS):

	Report No:	AD No:	
AEC	WT-606	467229	
	WT-1473	611262	u/2
	WT-501	514321	
	WT-301	479248	
	WT-1109	617182	u/2
	WT-1103	611254	u/2
	WT-1108	611321	u/2
	WT-1101	460280	u/2
	WT-1102	611253	u/2
	WT-1407	452637	u/2
	WT-1110	617155	u2
	~~WT-602~~	~~356274~~	completed
DASA	WT-1403	611257	u2
	WT-1614	355492	
	WT-1155	617170	u/2
	POR-2280	345753	
	WT-9003	342207L	u/2
	WT-1501	350279	replaced by AD-490150 ST-A now

The security office has **declassified** all of the listed reports. Further, distribution statement "A" applies to all of the reports.

FOR THE DIRECTOR:

(S)

JOSEPHINE B. WOOD
Chief, Technical Support

Security